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Reinforced earth retaining wall under vertical and horizontal strip loading.

Peter H. Seymour
University of Windsor

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REINFORCED EARTH RETAINING WALL UNDER VERTICAL AND
HORIZONTAL STRIP LOADING

by

Peter H. Seymour

A thesis
presented to the University of Windsor
in partial fulfillment of the
requirements for the degree of
Master Of Applied Science
in
CIVIL ENGINEERING

Windsor, Ontario, 1982

(c) Peter H. Seymour, 1982

To My Parents

ABSTRACT

This thesis investigates the behaviour of a reinforced earth retaining wall system under a surcharge strip loading. An experimental study was carried out on a model system with a granular backfill, reinforced with strips of steel. This model was instrumented with strain gauges to measure the strip stress, and dial gauges to record the wall deflection. The effects of both a vertical and horizontal load component were investigated. The results were used to interpret the mechanisms of behaviour of the system. This also included an investigation into the friction mobilized between the sand and the strips; a comparison between the theoretical and experimental results of the distribution of the maximum strip traction force as a function of depth; and comparisons between the theoretical models proposed for the distribution of horizontal stresses within the soil mass and the experimentally obtained values.

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NOMENCLATURE

Symbol	Represents
A	Cross-sectional area of backfill, reinforcing strips, (Kennedy et al.,(16)).
b	Width of reinforcing strips.
c	Soil Cohesion.
C_u	Coefficient of uniformity.
d	Distance from wall face to surcharge load, (Figs.2.9,2.11)
D_{10}	Diameter at which 10% of the soil is finer.
D_{50}	Diameter at which 50% of the soil is finer.
D_{60}	Diameter at which 60% of the soil is finer.
dh	Horizontal spacing of the reinforcing strips.
ds	Vertical spacing of the reinforcing strips.
dT/dl	Slope of tension distribution curve along strip.
e	Eccentricity of surcharge load.
E_t	Tangent modulus of soil backfill, (Duncan,(10)).
E_t	Tangent modulus of reinforcing strips, (Duncan,(10)).
f	Coefficient of soil-strip friction.
f_o	Coefficient of soil-strip friction as determined from a shear shear box test, (Bacot et al.,(4)).
F_r	Frictional resistance of strip, (Lee et al.,(7)).
h	Depth below surface.
H	Horizontal load component.
K	Coefficient of lateral earth pressure.
K_a	Coefficient of active lateral earth pressure.
K_o	Coefficient of at-rest lateral earth pressure.
K'	Modulus number, (Duncan,(10)).

l_e	Length of reinforcement effective in resisting pull-out of the strips.
n	Exponent determining rate of variation of initial tangent modulus with σ_3 , (Duncan,(10)).
P	Point load on surface.
P_a	Active earth pressure against vertical retaining wall.
P_o	At-rest earth pressure.
q	Vertical load component.
R	Reduction factor, (Kennedy et al.,(16)).
R_f	Failure ratio, (Duncan,(10)).
R_1	Scalar, (Fig.5.24).
R_2	Scalar, (Fig.5.24)).
T_{max}	Maximum strip traction force.
ΔT	Increment in strip traction force.

- GREEK -

α	Angle, (Figs.2.10, 5.24).
β	Angle, (Fig.2.10).
γ	Unit weight of soil.
δ	Angle, -(Fig.5.24).
π	= 3.1415926535897.
σ_1	Major principal stress.
σ_3	Minor principal stress.
σ_v	Vertical stress.
σ_h	Horizontal stress.
σ_v	Vertical stress at failure.
$\Delta\sigma_v$	Incremental vertical stress.
$\Delta\sigma_h$	Incremental horizontal stress.

$\Delta\sigma_s$ Incremental strip stress.
 τ Shear stress acting on strip.
 ϕ Internal angle of friction of the soil.
 ψ Angle of soil-strip friction.

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Chapter I

INTRODUCTION

1.1 GENERAL

The use of tensile stress resisting material in the form of fibres, straps, bars or boards in combination with soil has been in use for thousands of years, from rope fibres and bamboo shoots around which mud walls have been built, to the more familiar, and still current use of tree trunks in corduroy roads.

It was not until the 1960's that this age old concept began to be analysed and put to use in overcoming geotechnical problems, which would otherwise have required costly solutions. Vidal(29), a French engineer, working alone, pioneered the use of flexible reinforcing elements to improve the strength characteristics of sand. The association of the two materials resulted in a cohesive material he termed "Reinforced Earth".

Reinforced earth has since been used in foundation improvement, slope stability improvement and a variety of other situations, however its most widespread and best known use is in a retaining wall situation. Much research has been carried out into the behaviour mechanism of the reinforced earth retaining wall, and the most valuable work has been

that based on model studies or measurements made on full scale structures.

1.2 OBJECTIVE

This research looks into the behaviour of a reinforced earth retaining wall subject to a surcharge strip load aligned parallel to the wall head. The strip load has both vertical and horizontal components. The problem of a vertical surcharge load on the reinforced earth retaining wall system has widespread significance as it occurs in many situations such as, highway loads, railways, and other continuous dead loads. The situation wherein a reinforced earth retaining wall is subject to a horizontal load component occurs when the retaining wall system is used as a bridge abutment for a highway overpass. To the author's knowledge, no previous work has been conducted on this problem.

Furthermore, this work investigates the friction mobilized between the soil and the reinforcing elements; the maximum traction forces in the reinforcing elements; and the stress distribution occurring in the reinforced earth medium as a result of the horizontal surcharge load component.

1.3 SCOPE

In order to investigate the above aspects of the behaviour of the reinforced earth retaining wall system, extensive testing was done with a reinforced earth wall model. The model consisted of a Lake Erie beach sand backfill, reinforced with strips of metal, roughened to increase the friction between the sand and the strips. The strips were connected to the wall facing which was composed of thin steel channels. Some of the reinforcing strips were instrumented with strain gauges to record the strain developed in the strips due to the surcharge load. The deflection of the wall face was also monitored by dial gauges. Both the vertical and horizontal surcharge loads were applied through a mechanical loading apparatus set up about the model.

Results of this experimental work were analysed and used to explain the behaviour mechanism of the reinforced earth retaining wall system under the various loading conditions. These results were compared with design procedures currently in use for a reinforced earth retaining wall under a surcharge strip loading condition.

Chapter II

BACKGROUND AND LITERATURE REVIEW

2.1 GENERAL

This chapter introduces the principle of reinforced earth, and highlights the concepts fundamental to an appreciation of its behaviour, and sheds light upon a common misconception that reinforced earth walls operate upon a "tie-back" mechanism.

In addition, progress in the development of experimental and theoretical achievements in the case of the reinforced earth wall with and without a surcharge is summarized. A brief note on current design procedure is also included, which the reader will appreciate, is quite empirical, and is derived predominantly from experimental data rather than theoretical considerations.

Brief mention is also made of computer modelling of the reinforced earth wall, and attempts to describe the behaviour of reinforced earth as an ideal material in terms of a mathematical model.

2.2 BASIC PRINCIPLE

Reinforced earth is a composite medium. It consists of earth which is reinforced by sheets or strips of a material able to withstand large tensile stresses. The earth is, for the most part, a cohesionless, granular material, while the reinforcement generally is a series of metal strips laid out horizontally in the soil mass at regular horizontal and vertical intervals.

The object in placing the strips in the soil is to improve the mechanical properties of the medium by reinforcing it in the direction in which it is subject to the greatest tensile stresses.

The essential phenomenon in achieving this reinforcing effect is friction. Friction between the soil particles in contact with the reinforcing members allows stresses developed in the soil mass to be transmitted to the reinforcing members. This places the reinforcement in tension, thus introducing a form of lateral restraint to the composite medium. In order that this transmission of forces be effective, it is essential that there be adequate soil-strip friction without sliding.

The mechanism can be best understood by first considering an elementary cube of unreinforced earth, subject to unconfined compressive stresses in the vertical direction, σ_1 , as in Fig.2.1. Obviously this situation will

result in failure of the soil, unless a lateral restraining stress, $\sigma_3 = K_a \cdot \sigma_1$, is applied so that the Mohr's circle of stress becomes tangent to or falls below the failure envelope for the soil, Fig.2.2. In the absence of a reinforcing medium this stress, σ_3 , must be produced by external means in order to maintain the integrity of the soil mass.

Reinforcement is now introduced into the elementary cube in a direction perpendicular to the compressive stress, σ_1 , Fig.2.3. For the reinforcement to be effective, there must be no sliding between the reinforcement and the particles, so let us assume that the adjacent particles, A and B, are rigidly connected by the reinforcement. This will have the same effect as two plates connected by the reinforcement, capable of exerting lateral stresses on the cube. By applying a vertical stress, σ_1 , to the cube, and assuming no compressive stress has yet been mobilized at A or B, sliding of the particles with respect to each other is produced. The cube begins to compress in the σ_1 direction, and since the particle mass occupies a volume which is roughly constant, it will expand in the direction of the reinforcement. This expansion is accompanied by an extension of the reinforcement. Sliding of the particles within the cube will stop when

the compressive forces, exerted by the particles at A and B and equivalent to σ_3 , become large enough so that the Mohr's circle becomes tangent to the failure envelope for the soil, Fig.2.2. Thus the reinforcement has the effect of providing an internal source of lateral restraint to the soil mass."

Tests performed by Schlosser(25), on triaxial specimens of sand reinforced with strips of metal have successfully shown that the reinforced medium does indeed exhibit an effective cohesion under uniaxial compression.

It is clear from the above discussion that fundamental to a clear appreciation of the behaviour of reinforced is an insight into the role of soil-strip friction. To this end various studies have been performed.

Schlosser and Vidal(26) performed shear box tests on metal strips with different degrees of roughness. They concluded that the presence of ribs on the strip surface enables almost full mobilization of internal friction of the soil, and this is the type of strip currently in use in practice.

This result was also confirmed by Bacot et al.(4), who conducted several types of tests to determine factors affecting soil-strip friction. From the results of reduced scale model tests on a reinforced earth retaining wall, they give the soil-strip friction coefficient, f , as a function of the coefficient of

friction obtained from a shear box test, f , the reinforcement length, l , and breadth, b :

$$f = f_0 + \alpha l + \beta/b \quad \dots 2.1$$

with α and β constants.

This relationship was verified by Schlosser and Elias(24), who also looked at the effects of density and overburden pressure on the friction coefficient. In particular they noted that tangential stresses exerted by reinforcement on a dense soil will cause the soil to dilate, which causes an increase in the normal stresses on the reinforcement, resulting in a higher value of soil-strip friction. They also noted that the friction angle will decrease with increasing overburden pressure.

Assuming the coefficient of friction to be related to the ratio (σ_v / σ_{vf}) where σ_v is the existing vertical stress and σ_{vf} is the vertical stress at failure, Kennedy et al.(16) proposed the following relationship for the friction coefficient:

$$f = (\sigma_v / \sigma_{vf}) \cdot \tan \psi \quad \dots 2.2$$

where ψ is the angle of soil-strip friction, and the ratio (σ_v / σ_{vf}) may be taken as $(1/\text{factor of safety})$.

The values currently in use in the design of reinforced earth structures, as outlined by McKittrick(18), are as follows:

for smooth strips: $f = 0.4$

for ribbed strips: $f = \tan \phi$, for $h \geq 6m$.

$$f = f_0 + (h/6)(\tan \phi + f_0), \text{ for } h \leq 6m \quad \dots 2.3$$

where ϕ is the angle of internal friction of the soil, h is the depth below the surface. The coefficient f_0 depends upon a number of parameters (angularity, surface texture, angle of internal friction). It may be expressed as follows:

$$f = 1.2 + \log C_u \quad \dots 2.4$$

where C_u is the coefficient of uniformity $= D_{60} / D_{10}$, where D_{60} and D_{10} are the diameters at which 60% and 10% respectively of the soil is finer, by weight.

2.3 REINFORCED EARTH IN RETAINING WALLS

One of the widest applications of the reinforced earth system is in retaining walls. As has already been made clear, reinforced earth possesses an effective cohesion in the direction in which the reinforcing elements lie. This makes it an ideal material for use in a retaining wall situation.

Considering a semi-infinite cohesionless soil mass with a horizontal surface behind a rigid non-moving retaining wall, Fig.2.4, the pressure, P , exerted by the wall on the soil at any depth, h , in order to maintain the soil in the at-rest condition, is given by:

$$P_0 = K_0 \cdot \gamma \cdot h \quad \dots 2.5$$

where γ is the unit weight of the soil, and K_0 is the coefficient of earth pressure at rest.

The same soil mass reinforced with horizontal reinforcing strips in the direction perpendicular to a retaining wall, Fig.2.5, does not require an externally applied pressure, such as P_0 , in order to maintain its state of stress in an at-rest condition. The pressure thus required is developed internally in the soil mass and transferred to the reinforcing strips, through friction. The strips are placed in tension, and it is this tension which maintains the soil mass without the need for externally applied loads.

Vidal(28) suggests that the shear stresses are transmitted, from the grains in contact with the strip, to the soil, in the form of a strut or arch, Fig.2.6. The exact nature of this effect is not known with any certainty, and consequently the actual state of stress existing within the soil is difficult to ascertain.

Along this vertical section, Fig.2.5, some sort of protection is required to maintain the integrity of the soil at the extremity of the reinforcing strips. To this end a "skin" is affixed to the end of the reinforcing strips, in order to prevent any erosion or spillage of the soil.

It will be of help to the reader to discuss briefly the three constituents of a reinforced earth retaining wall.

2.3.1 The Soil

The type of soil used is a free-draining granular material. there are two reasons for this:

1. To prevent any build-up of pore water pressure in the backfill which would reduce the shear strength of the soil.
2. To enable an appreciable amount of friction to be developed between the soil and the reinforcing strip.

Current design specifications recommend that 25 % be the maximum percentage by weight of the backfill material passing the no.200 (.074 mm opening) sieve size. In all cases the soils used are classified as non-plastic. The effect of clay content has been considered elsewhere(18).

2.3.2 The Reinforcing Strips

These are made of galvanized steel and are usually ribbed in order to increase the soil-strip friction. The design yield stress is taken as two thirds of the actual yield stress as determined experimentally. Galvanized steel is used, as when the zinc corrodes it

leaves an insoluble protective layer which prevents further corrosion of the metal. Details of this problem have been studied by Darbin et al.(9).

The reinforcing strips are bolted to the skin elements and laid horizontally over the backfill at predetermined vertical and horizontal spacings.

2.3.3 The Skin

This effectively is all the passer-by sees of the reinforced earth system. It has a minor structural role in preventing local erosion of the soil backfill. It may be made of any material, metal, plastic, even sackcloth has been used, however most frequently interlocking precast concrete panels are used. These panels must have the ability to move relative to one another in order to accomodate differential settlement along the length of, or perpendicular to the wall.

2.4 REINFORCED EARTH WALLS WITHOUT SURCHARGE

In dealing with the stability of the reinforced earth wall structure there are two basic problems.

2.4.1 Consideration Of The External Stability

The overall dimensions of the structure must be considered along with any external loading conditions, Fig.2.7, to determine the degree of settlement and factor of safety against overturning, bearing capacity failure and sliding.

Details of this analysis will not be considered herein.

2.4.2 Analysis Of Internal Stability

This is the aspect of reinforced earth which has received most attention from researchers, as the exact behaviour of a reinforced earth wall is very complex, and many of the mechanisms are as yet still not fully understood. However, reinforced earth retaining walls have been built for almost fifteen years and successful design procedures have been formulated based on simplifications and selection of conservative parameters.

Since Vidal(29) introduced the concept of reinforced earth for retaining walls, researchers have been consistent in describing the predominant failure modes:

1. Failure due to lack of tensile strength of the reinforcing strips.
2. Failure due to insufficient soil-strip friction, i.e. slippage of the reinforcing strips.

3. Breakdown of the so-called arching effect, Fig.2.6, i.e. shear failure of the granular matrix between the strips. This type of failure has been studied elsewhere by Shen et al.(27).

Lee et al.(17), recognized the significance of the above failure modes and interpreted the mechanism of failure in terms of Rankine earth pressure theory. They assumed an active earth pressure distribution on the wall face, and that the maximum tie tension, T_{max} , at any depth, h , below the surface is given by:

$$T_{max} = K_a \cdot \gamma \cdot h \cdot ds \cdot dh \quad \dots 2.6$$

where ds and dh are the vertical and horizontal spacings of the reinforcing strips, and K_a is the coefficient of active earth pressure. They also assumed that the maximum tension in the strip occurs at the wall face.

On the basis that an active failure zone had been formed, the reinforcing strips were assumed to offer resistance against pull-out only in the soil mass beyond the failure zone defined by the angle $(45^\circ + \phi/2)$. Thus the frictional resistance, F_r , of a strip at any depth, h , below the surface:

$$F_r = 2 \cdot b \cdot l_2 \cdot h \cdot f \cdot \sigma_v \quad \dots 2.7$$

where l_2 is the length of the strip beyond the failure zone, i.e. the length of the reinforcement effective in resisting pull-out.

However Juran(14) argued that:

the classical retaining wall design methods.....are inadequate to describe the fundamental aspects of the model failure mechanism, and more particularly: 1) The coexistence of an 'active' and 'resistant' zone, 2) The effect of the interaction between the soil, strip, and skin on the state of stress within the reinforced earth mass.

Similar conclusions are reached by Hausmann and Lee(13), and Schlosser and Long(25), who viewed the reinforced earth system as distinct from an anchorage technique, the latter authors refer to an observed strip tension variation as shown in Fig.2.8. This type of distribution has been confirmed by many measurements taken on instrumented walls,(3),(21),(25). This distribution has the following characteristics:

1. The strip tension at the wall face is only a fraction of the maximum strip tension.
2. The points of maximum tension in the different layers of reinforcement lie on a parabolic curve.

Several other configurations of this curve have been proposed by different authors; Juran and Schlosser(14), suggest a logarithmic spiral, whilst Basset and Last(6), see it as being vertical and parallel to the wall down to 80 % of its depth, thence joining the base of the wall in a straight line.

This curve defines the boundary between an active and resistant zone. In the active zone the tangential stresses

exerted by the earth on the reinforcement are directed towards the wall, Fig.2.8, whilst in the resistant zone they are directed away from the wall, and here the earth tends to retain the reinforcement.

The tangential component, τ , of the stress exerted by the earth on each face of the reinforcing strip is:

$$\tau = (dT/dL)/2.b \quad \dots 2.8$$

where dT/dL is the slope of the tension curve. Schlosser also suggested that in the active zone the coefficient of friction mobilized along the reinforcement was close to the actual value of fully mobilized soil-strip friction.

Based on results from an instrumented full-scale structure, Shen et al.(27), proposed that the state of stress in a reinforced earth wall approaches the at-rest condition. This was also suggested by Chang and Forsyth(8). However more extensive field observations made by Baquelin(5), indicate that the coefficient K near the surface is closer to K_0 , decreasing to a value smaller than K_0 , over a depth of 6 metres, Fig.2.14. Juran et al.(15) also reach a similar conclusion.

A finite element approach was also considered by Al-Hussaini and Perry(3), assuming a hyperbolic stress-strain behaviour for the earth fill and assuming the behaviour of the reinforcing strips and facing elements to be linear elastic. Harrison and Gerrard(11), suggest considering the

reinforced earth mass as consisting of soft layers reinforced with closely spaced thin stiff layers. This theoretical model is only applicable to reinforcing by sheets. In order to account for reinforcing by strips Gerrard and Wardle(11), have used orthorhombic elastic theory to present an analysis of the stress-strain behaviour under several loading conditions. However their analysis is only for a semi-infinite half-space, hence suitable boundary conditions need to be incorporated to account for a retaining wall situation.

2.5 REINFORCED EARTH WALLS WITH SURCHARGE

In many instances the reinforced earth structure will be built to support an imposed load, such as in the case of highways, railroads, and most frequently, bridge abutments.

2.5.1 Vertical Load

The effect of a vertical load is to increase the tension in the reinforcements, by increasing the vertical stress throughout the soil mass. Measurements made on models(21), and on a full scale structure in Dunkirk, France(5), have shown that the additional vertical stress is spread in the reinforced earth mass at a slope of 2:1.

Schlosser and Long(25) reported on theoretical and experimental work conducted on the effect of a line load acting on the head of a reinforced earth retaining wall and

parallel to it. They also assumed the load to disperse as a uniform stress within the 2:1 dispersion lines, Fig.2.9. The additional tension in the reinforcement, ΔT , induced by the surcharge effect, was given by:

$$\Delta T = K_a \cdot ds \cdot dh \cdot (P/[d + h/2]) \quad \dots 2.9$$

However this analysis is still based on the Rankine coefficient of active earth pressure, and as such is not truly representative of the reinforced earth medium. Al-Hussaini and Perry(3), carried out a field test on an instrumented reinforced earth wall subjected to a surcharge load uniformly distributed over the surface. They also assumed the behaviour of the system to follow Rankine earth pressure theory, which led to a lack of agreement between the experimental and theoretical results.

Kennedy et al.(16), present an analysis to estimate the maximum tension in the reinforcement when the reinforced earth retaining wall is subjected to a surcharge strip load. T_{max} is deduced from a modification of Terzaghi's formula (based on elastic theory) for the computation of the lateral pressure, σ_h , Fig.2.10, against a conventional rigid retaining wall:

$$T_{max} = (2-R) \cdot q \cdot (\beta - \sin[\beta] \cdot \cos[2\alpha]) \cdot ds \cdot dh / \pi \quad \dots 2.10$$

where R is a reduction factor based upon the stiffness of the separate media.

2.5.2 Horizontal Load

To the knowledge of the author very limited work has been carried out to determine the effect of a horizontal surcharge load applied on the soil surface, on the behaviour of a reinforced earth retaining wall. A horizontal component directed towards the wall face can have a significant effect on the internal stability of the wall, as it will result in a large increase in strip tension in its region of influence. The French Ministry of Transport(20), have proposed a method of incorporating this effect into design, which is summarized in Fig.2.11, where $\Delta\sigma_w$ is the change in horizontal stress due to the horizontal surcharge load:

$$\Delta\sigma_w = H.(1 - h/h_0)/(1 + d) \quad \dots 2.11$$

H is the horizontal load component, h is given as a function of ϕ , the internal angle of friction of the soil, and e is the eccentricity of the resultant of the vertical and horizontal load component. As yet there has been no data published to support this proposition.

2.6 SUMMARY OF DESIGN PROCEDURES

In designing for the internal stability of reinforced earth retaining walls, two failure modes are considered:

1. Slippage due to lack of adherence between soil and strip.
2. Tensile failure of the reinforcement.

The factor of safety against slippage should be ≥ 1.5 , and against tensile failure ≥ 2.25 . This is to ensure that slippage will always occur prior to tensile failure, which is a catastrophic type of failure.

The factor of safety against failure by lack of adherence is:

$$F.O.S. = (2 \cdot b \cdot f \cdot l_c) / (K \cdot ds \cdot dh) \quad \dots 2.12$$

where l_c , f and K are defined in Figs. 2.12, 2.13, 2.14.

The factor of safety against rupture of the reinforcement is:

$$F.O.S. = T / (K \cdot \sigma_v \cdot ds \cdot dh) \quad \dots 2.13$$

where σ_v is the vertical stress at any depth, h .

These two factors are checked at every level, and changes accordingly made to l_c , b , ds or dh . Similar factors have previously been proposed by Hausmann and Lee(13).

2.7 OTHER APPLICATIONS

Earth reinforcement is an extremely versatile mechanism and its applications are by no means limited to a retaining wall situation with steel ties and concrete facing panels.

A significant amount of work has been conducted by several researchers into the improvement of bearing capacity of a granular medium. Binquet and Lee(7), reporting on model test results from a sand reinforced with strips of metal,

indicate that the ultimate bearing capacity and settlement characteristics of a soil can be improved by a factor of two to four times that of the unreinforced medium. Akinmusuru and Akinbolade(1), concluded that ultimate bearing capacity values can be improved by a factor of up to three. The reinforcing medium used in their model tests was a rope fibre material, chosen because of its suitability for low cost projects in developing countries. Tests performed by Bassett and Last(6) on sand reinforced with rods aligned with the principal tensile strain directions under a footing also indicated a significant improvement in the ultimate bearing capacity. Rea and Mitchell(23) conducted bearing capacity tests on a sand reinforced with a grid of interconnected paper cells and concluded this method of reinforcing to be a cheap and effective way in improving the ultimate bearing capacity of the sand.

Fabrics are also used to improve ground conditions for a variety of geotechnical problems. The problem of excessive shear stresses induced at the base of a high embankment by the tendency of the embankment to spread have been successfully dealt with by reinforcing the critical area with woven nets of synthetic resin. Wager and Holtz(30) have also dealt with the same problem by using beams or channel sections tied together by a tie rod, at the base of the embankment, Fig.2.15.

Chapter III

EXPERIMENTAL INVESTIGATION

3.1 GENERAL

Much of the experimental work performed on reinforced earth retaining walls has been carried out on model walls. Vidal (29), recommended the use of model tests in order to complement theoretical work.

The aim of the experimental work conducted was to provide a working model of the reinforced earth retaining wall system. It must be noted that the model was treated as a small structure, taking into account the actual dimensions and strength of the individual components. Certain elements of the model used were different than those used in actual practice, as the priority was to provide a model which in its most essential aspects will behave as the full-scale structure.

3.2 BASIC ELEMENTS OF THE MODEL

3.2.1 Containment Box

The box in which the reinforced earth structure was constructed was made of 12.7 mm thick sheets of plexiglass and measured 0.556 m wide by 0.749 m long by 0.57 m high, Fig.3.1. The actual reinforced earth retaining wall system

itself measured 0.706 m long by 0.53 m high by 0.536 m wide. These dimensions provide sufficient height to study the stress conditions at several horizontal levels, and sufficient width to minimize the effect of side wall friction at the centre of the box where all measurements are taken. Plexiglass lends a smooth surface and thus minimizes friction with the sand along the sides of the box. A steel frame was placed around the box in order to prevent excessive arching of the side walls.

The box sat upon a metal base frame, to which was rigidly bolted an electrically driven vibrator.

3.2.2 The Sand

The sand used as the backfill material was a Lake Erie beach sand, ordinarily used for making concrete. Grains larger than 2.4 mm in diameter were removed in order to prevent damage to the strain gauges. The resulting grain size distribution curve is shown in Fig.3.2. It had a mean grain size, $D_{50} = 0.31$ mm, and a coefficient of uniformity of 2.3. In accordance with current design procedure, McKittrick(18), the percentage by weight of the sand passing the No. 200 sieve was below a maximum value of 25 %, being only 1 % in this work. From a direct shear test, the angle of internal friction of the soil was determined to be 40° , as in Fig.3.3. The specific gravity of the sand was 2.65 and the unit weight

kept constant at a value of 17.1 KN/m^2 . This represented a medium-dense to dense condition for the sand used, thus ensuring that dilation would occur during shear, and is concurrent with present design procedures as outlined by McKittrick(18).

3.2.3 The Reinforcing Strips

The reinforcing strips used were made of shim steel manufactured by Paxam Metals Ltd.. They measured 0.025 mm thick by 25 mm wide by 665 mm long. The strip lengths were selected to be greater than 0.8 times the height of the wall, the minimum ratio allowed in design. Other dimensions chosen were based on work done by Mossaad(21) on a similar model configuration. Preliminary load tests on the reinforced earth wall indicated failure of the system by soil-strip slip at relatively low loads, so it was decided to glue sand to the top and bottom surfaces of the strips in order to increase the soil-strip friction. This permitted a higher loading of the system, enabling a greater range of measurements to be taken.

The strips were glued to small plates of galvanized steel which were attached to the skin elements with 3.2 mm diameter bolts.

On the uppermost channel three strips were attached at mid-height, Fig.3.1, to prevent this channel from coming away from the wall. Seven of the ten strips located at the

wall centre were instrumented with strain gauges, the gauges being affixed prior to sand being glued to the strips. The centre strips were chosen, so as to minimize the effects of friction of the sand mass on the side walls.

Several stress-strain tests were performed to determine the range of stresses in which the smooth strips behaved elastically in tension. These tests indicated that the stress-strain relationship is linear up to a stress value of $4.5 \times 10^8 \text{ N/m}^2$. Results of a test on a strip which was also instrumented with five equally spaced strain gauges, are presented in Fig.3.4. The difference in the strain values at given stress levels can be attributed to slight misalignments in the strain gauges with respect to the long axis of the strip.

3.2.4 The Skin Elements

The skin elements were made of galvanized steel channels, 50 mm high by 12.5 mm flange width and 0.5 mm thick, Figs.3.5 and 3.6. They spanned the width of the box with a small clearance at either side to avoid friction with the side walls. Pieces of foam rubber were glued on the back of the channels at either end in order to prevent sand spilling out from the clearance.

Ten channels were used to build up the wall. They were bolted to each other at the flanges, using 3.22 mm diameter bolts, at the points where the strips were attached to the

channels. The channels were arranged with the flanges facing out from the sand in order to present a flat vertical surface to the sand. Strips of foam rubber were glued along the flanges to prevent any sand from escaping from between the channels.

3.3 MEASURING INSTRUMENTS

3.3.1 Strain Gauges

The strain gauges were of type EA-06-250BG-120 of 120 Ohms (0.3 %) resistance and a gauge factor of 2.03 (0.5 %) at 75° F. They had a strain limit of 5 %.

Before applying the gauges to the strips, the strip surface was prepared using acetone, a conditioner and neutralizer, and then the gauge was fixed to the surface with M-Bond 200 adhesive according to the procedures laid down by the manufacturer. Lead wires were then soldered to the gauges and the gauges coated with M-Coat A, a polyurethane coating followed by M-Coat D, a protective coating to prevent damage to the gauges from abrasion with the sand.

The strain gauges were calibrated by conducting tensile stress-strain tests on the instrumented strips. Full details of the calibration procedure and results are given in Appendix III.

The locations of the strain gauges are as shown in Fig.3.7. Gauges were placed right at the wall face to give an indication of the pressure acting on the skin elements.

They were also placed along a line joining the base of the wall to the inside of the load block for load location II, as this line was assumed to be the boundary of the active and resistant zones for the load at location II. Thereafter, the gauges were evenly distributed along the strip length. No gauges were placed at levels 7 and 9, as these were not considered critical under conditions being investigated; neither were there gauges at the free ends of the strips, where strip tensile stresses are zero.

The gauges were connected to a Vishay Ellis V/E 20-A electronic strain gauge indicator and V/E 22 automatic printer, by eight V/E 21 switch, balance and calibration units capable of reading up to 80 gauges simultaneously, Fig.3.8. In this work, only 39 strain gauges were used, as using too many might have interfered with the behaviour of the system.

3.3.2 Dial Gauges

Ten dial gauges, reading to an accuracy of 0.001 of an inch, (0.0254 mm), were placed at the wall front to record the wall movement, Fig.3.9. Each dial gauge was located at the centre of each channel along the centre line of the wall.

3.4 CONSTRUCTION PROCEDURE

The reinforced earth retaining wall model was built up in a series of layers. The same general procedure was followed in all tests.

The lowermost channel was placed on the floor of the box, with its flanges facing outwards, and held in place by two wooden posts. A predetermined weight of sand, (to ensure a unit weight of 17.1 KN/m^2) was poured in behind the channel. The electrical vibrator was switched on and the sand surface made horizontal by trowelling it flush with the top of the channel. Three strips were then placed along the sand surface at 203 mm horizontal intervals, with one end lying over the flange of the channel. The next channel was placed on top, Fig.3.10, and the two channels and strips bolted together. In placing the instrumented strips the wires were laid along the sand at the side of the strips so as not to interfere with the soil-strip interaction. More sand was placed on top of this first layer and the procedure repeated until the reinforced earth wall had been fully constructed. Then the wooden posts were taken away from the front of the wall and the dial gauges and strain gauges were all set to zero, and the model was ready for loading. Upon removal of the supporting wooden posts the system remained stable and after all gauges had been zeroed there was no detectable creep.

3.5 LOADING MECHANISM

The arrangement used to apply the load on the surface of the reinforced earth retaining wall backfill is shown in Figs. 3.11 to 3.13. It consisted of a metal block, 106 mm, in cross-section which was placed on the sand surface, parallel to the wall face, and spanning almost the whole width of the box. A leverage system, Fig.3.11, was then used to apply the load on the block, in which dead weights were suspended from the end of a metal beam by a hanger. A metal frame bolted to the floor provided the reaction required to keep the system in equilibrium. The load was applied centrally on the block through a 25.4 mm diameter steel rod with its longitudinal axis lying directly above the central axis of the block, Fig.3.14.

In order that the horizontal force on the block be fully transmitted to the soil mass it was required that friction with the vertical load component be minimized. This was achieved by attaching to the top of the block two plates capable of moving relative to each other on frictionless runners, Fig.3.14. Coarse abrading paper was glued to the base of the loading block to further effect the load transmission to the soil.

3.5.1 Loading Procedure

3.5.1.1 Vertical Load

To apply the vertical load the loading apparatus was set up as described, the loading block placed on the soil surface and the beam positioned to take the weights. Calculations had been prepared prior to loading to determine the vertical load on the soil surface due to the weights placed on the hanger at the end of the beam. The maximum vertical load applied to the model corresponded to a stress of 100 KN/m^2 under the footing. This compares favourably with actual live loads in the region of 80 KN/m^2 as measured by Juran et. al.(15), on a bridge abutment, and tests performed by Al-Hussaini and Perry(3) who loaded their wall up to 90 KN/m^2 .

3.5.1.2 Horizontal Load

These loads were applied in two directions:

1. Towards the wall face.
2. Away from the wall face.

In the former case, the model was positioned so that the wall faced towards the end of the base frame to which the pulley was affixed, Fig.3.12, and in the latter, the model was simply turned around the other way, Fig.3.13.

Preliminary testing indicated that the maximum ratio of horizontal to vertical load was in the region of 0.42. Above this value local shear failure of the soil-reinforcement

system in the immediate vicinity of the strip load occurred due to an excessive inclination of the resultant. In order to prevent this from upsetting the experimental programme it was decided to keep the maximum value of this ratio to approximately 0.33.

Horizontal load components towards the wall face were kept smaller than those away from the wall for similar vertical loads, especially for load locations close to and at the wall face.

In applying the loads, care was taken to apply the loads slowly and in small increments, so as to allow time for the stresses to propagate through the reinforced earth mass, and to avoid disruption of the medium. This was especially important in applying the horizontal loads.

3.6 TESTING PROGRAMME

The programme was formulated to investigate the effects of vertical and horizontal loads on a reinforced earth retaining wall with direct reference to the system as a bridge abutment. From preliminary tests, stresses in the strips due to the weight of the soil alone were found to be quite small, so in taking the measurements, the weight of the soil as a contributing factor to development of the stresses in the strips was not considered, as this effect has been studied elsewhere, (3), (21), (25). To this end, all measuring devices were zeroed after wall construction.

Four load locations were considered, Fig.3.15 :

1. Location I : The load is at the wall face, this represents the most critical position, which could produce a local failure near the top.
2. Location II : The load is at the middle of Rankine's active failure zone.
3. Location III: The load is just inside the Rankine failure zone.
4. Location IV : The load is just outside Rankine's failure zone.

The Rankine wedge was chosen as an arbitrary reference point for the load location, and as such the $45 + \phi/2$ line is not intended to represent the boundary between the active and resistant zones.

At each location a vertical load was first applied, ranging from 60 KN/m^2 to 100 KN/m^2 . In some cases, the strain and wall deflection readings were taken at load increments up to the fully applied vertical load.

Once the vertical load was applied and all readings taken, the horizontal load was applied. In all cases, the horizontal load was applied in several increments, and readings taken at each load increment, in order to give a picture of the developement of stresses in the strips due to the application of the horizontal load. Table 3.1 summarizes the experimental programme.

A preliminary test was conducted in order to determine the vertical surcharge load at which the wall would fail, so that this situation would not occur during the experimental programme. The load was positioned at load location II, and a vertical surcharge only was applied. The reinforced earth system failed at a surcharge load of 314 KN/m². This ensured that the system would not fail during the subsequent testing programme, wherein the maximum vertical surcharge load was 100 KN/m².

Chapter IV

PRESENTATION AND DISCUSSION OF EXPERIMENTAL RESULTS

4.1 INTRODUCTION

This chapter presents, discusses and attempts to interpret, the results obtained from the experimental work performed with the reinforced earth retaining wall model.

Results from preliminary tests are not presented, as these experiments were conducted solely to test the set-up and to determine limits within which the experimental work could be conducted. As such, the results of this preliminary work are incorporated into this chapter.

The results dealt with in this chapter pertain to the behaviour of the reinforced earth retaining wall system under a vertical load, at four different load locations, and subsequent application of a horizontal load component.

The work was confined to an investigation of the behaviour of the system under externally applied loads, and did not investigate the stresses developed in the reinforcing strips due to the soil pressure only, as extensive work has been conducted to this end. Moreover, the relatively small dimensions of the reinforced earth retaining wall system used, prevented a practicable investigation of this latter aspect of its behaviour.

4.2 TRACTION FORCE DISTRIBUTION IN THE STRIPS UNDER A VERTICAL LOADING

In considering the effect of a vertical surcharge strip load on the internal stability of a reinforced earth retaining wall, strip loads close to the wall are most critical. Surcharge loads in this region contribute to the formation of a failure wedge within the reinforced earth mass. This results in a characteristic traction force distribution along the reinforcing strip length. When the surcharge load does not contribute to the formation of a failure wedge, as in load location IV, the traction force distribution has a different shape.

The strip load at location II represented an average position contributing to the formation of a failure wedge, and is fairly typical of full scale situations where the reinforced earth system is used as a bridge abutment.

The tensile stress and traction force distribution curves for load location II are shown in Figs. 4.4 to 4.8, and the measured stresses are presented in tables 4.4 to 4.11. The results show the stresses and traction force due to the vertical surcharge load only, as the values due to the initial soil pressure are not included. Knowing the stress-strain relationship for each gauge (see Appendix III), and the cross-sectional area of the strips, the strain values were converted to stress and thence from stress to traction (tensile) force. Since the cross-sectional area of the strips remains constant, the same distribution may be used to represent both tensile stress and traction force.

Considering the traction force distribution curves, (Figs. 4.2 to 4.12), the ordinates, which represent the traction force at any point along the strip, follow the same pattern for each strip at each level, namely: from a non-zero value at the wall face the traction force increases to a maximum, at some distance along the strip from the wall face. This distance, as can be seen from the figures, varies with depth. From this maximum value the traction force then reduces along the length of the strip to zero at the free end. Upon closer inspection, this distribution has certain definite characteristics which are evident in every strip. These are:

1. The traction force measured at the wall face is not a maximum, and is non-zero.
2. Moving away from the wall, the traction force increases to a maximum value at some distance along the strip from the wall face. The location of the point of maximum traction force will vary with the depth of the strip and the load location.
3. Beyond the point of maximum traction force, the force decreases linearly (at the same rate as it increases from the wall face) over a certain portion of the strip length, and thereafter
4. The rate of decrease is reduced as the force decreases to zero at the free end of the strip.

This type of force distribution curve has been observed in previous work (3),(21). Kennedy et. al. (16) have proposed an idealized distribution for it.

The distribution is justified as follows: The vertical strip load applied on the surface of the sand will result in distribution of vertical stresses within the mass as proposed by Boussinesq. Boussinesq's distribution can be approximated by assuming that the vertical stress is contained within the 2:1 dispersion lines, wherein it varies only with depth, and outside this region the vertical stress may be considered negligible, Fig.4.1. From a consideration of static equilibrium of the vertical stress in the soil, σ_v , and the traction force T , in the reinforcing strip, the following relationship is obtained:

$$dT/dl = 2 \cdot b \cdot f \cdot \sigma_v \quad \dots 4.1$$

where dT/dl is the slope of the traction force distribution along the strip, and b and f are as defined in section 2.2. Hence the slope of the traction force is in direct proportion to the vertical soil stress. Since the vertical soil stress is assumed to be constant within the 2:1 dispersion lines, the slope of the traction force distribution curve should have a constant value in this region. However, as can be seen from all the figures, it is the magnitude of this slope which remained unchanged, as the slope changed from a positive to negative value within the region of the 2:1 dis-

persion lines. The reason for this is that upon application of the load, a failure wedge was formed (somewhat akin to the Rankine active wedge), which tended to move laterally towards the wall. Consequently, within this wedge the frictional stresses exerted by the soil on the strips were directed towards the wall, whereas in the resistant zone they were directed away from the wall. Thus the value of the slope changed from positive to negative across the boundary from the active to the resistant zone, whilst the magnitude of the slope remained approximately the same value throughout. This is particularly noticeable at level 4 in Figs. 4.4 and 4.6 to 4.8. The traction force, being the summation of the frictional stresses of the soil on the strip, increased from its value at the wall face to a maximum, due to the application of these frictional stresses in a direction towards the wall face, Fig. 2.8. Once the frictional stresses were directed in the opposite direction the traction force reduced from its maximum value, until it became zero at the free end of the strip.

Outside the 2:1 dispersion lines the vertical stress in the soil due to the surcharge load was greatly reduced; thence from equation 4.1, dT/dL will be much smaller, and this can be verified from the distributions in Figs. 4.4 to 4.8. This effect was especially noticeable in Fig. 4.5 and also in the uppermost strip in each of the tests, but less so in the lower strips. This may be explained by considering

the Boussinesq distribution of vertical stresses in the soil, Fig.4.1. From the diagram one can see that at shallow depths relative to the width of the load, the vertical stress quickly reduces to zero outside the 2:1 dispersion lines, but at greater depths the reduction to zero is less pronounced.

The magnitude of the traction forces at all points along the strips, as can be seen for example by comparing Figs.4.4 and 4.7, was proportional to the magnitude of the surcharge strip load.

For different surcharge loads, but at the same load location, the overall shape of the traction force distribution remained similar for each strip, whilst the magnitude of the traction force increased. It is worthwhile to note that the greatest proportionate increase in the magnitude of the traction forces occurred within the 2:1 dispersion lines.

4.2.1 Load Applied at Various Locations

As previously mentioned, the position of the load will affect the shape of the traction force distribution curve. For the load at locations I, II and III the distribution is essentially the same, with little overall differences, however there is a departure from this type of distribution for the load at location IV.

4.2.1.1 Load at Location I

Traction force and stress distribution curves for the load at the wall face are presented in Figs. 4.2, 4.3 and the stresses for all three tests conducted with the load at the wall face are presented in tables 4.1 to 4.3. From the figures it is again evident that outside the 2:1 dispersion lines the slope of the traction force distribution was less than inside, for the same reason as previously discussed. However in this instance the position of maximum traction force was much closer to the wall face. Another and even more significant observation is that the values of the traction force at the wall face, and the maximum traction force on every strip were greater than their corresponding values for the same vertical load at location II.

4.2.1.2 Load at Location II

This case has already been discussed, as the traction force distribution along the strips in this case is exemplary of the situation wherein a potential failure wedge is formed by the application of the load on the soil surface.

Traction force and stress distribution curves for the load in this location are presented in Figs. 4.4 to 4.8 and the strip stresses for all the tests are given in tables 4.4 to 4.11.

4.2.1.3 Load at Location III

Traction force and stress distribution curves for this case are shown in Figs. 4.9 and 4.10, and the strip stresses are presented in tables 4.12 to 4.15. Notice that here the maximum stresses in the strips were located further away from the wall than in the previous two instances where the loads were closer to the wall. In addition, the traction forces at the wall face and the value of the maximum traction force were less than their corresponding values for the same surcharge loads at location II, as may be observed by comparing Figs. 4.9 to 4.4 and 4.10 to 4.7.

4.2.1.4 Load at Location IV

Here the traction force distribution along the strip departed from the configuration peculiar to the first three load locations. As may be seen from Figs. 4.11 and 4.12 the traction force did not increase linearly to its maximum value with distance from the wall. Outside the 2:1 dispersion lines the rate of increase was small, but it immediately increased once inside the 2:1 dispersion lines; this was especially evident in the upper strips as in Fig. 4.12. As in the previous load locations, the traction force decreased beyond the maximum at a similar rate as it increased, within the 2:1 dispersion lines. Beyond this region the traction force decreased at a smaller rate than within, to zero at the free ends. The value of the traction force at the wall face was

virtually zero for the load in this location hence the existence of the wall was of little or no consequence in influencing the traction force in the strip due to the surcharge load applied in this position. In effect, this situation may be considered approximate to that in which a load is applied on a semi-infinite reinforced soil mass. The values of maximum traction force on each strip for the load in this location were again lower than those for the same vertical load at location III, as may be observed by comparing Figs. 4.11 to 4.9 and 4.12 to 4.10.

4.3 LOCATION OF THE FAILURE PLANE

As already mentioned, a so called failure wedge was created upon application of the strip load on the soil surface. The wedge is delineated by the points of maximum traction force in the strips. However, due to the limitations of the experimental work, the exact location of the maximum traction force in the strip was difficult to ascertain. Yet in most cases the positions of the maximum traction force did coincide with what may be assumed to be a failure plane.

The location of the failure plane will depend upon the location of the surcharge load. This is mentioned by Schlosser and Long (25), and was confirmed in this experimental work. Fig. 4.13 shows the points of maximum traction force for the situation where the strip load was at the wall face. Clearly, in this case, the locus of maximum traction forces

may be approximated by a straight line joining the base of the wall to the inside edge of the strip load. This approximation may also be used to define the failure wedge formed by the strip load at location II, Fig. 4.14, the points of maximum traction force again being on the straight line joining the base of the wall to the inside of the strip load. In this case, the gauges lay along the assumed failure plane, which caused the maxima to coincide exactly with the straight line, whereas for load location I, the gauges were slightly offset from this line, but it is noted in the former case that it was the gauges nearest the straight line which registered maximum values.

For load location III, the straight line approximation held for all the instrumented strips, save the top and bottom strip, Fig. 4.15, and for load location IV the straight line approximation further departed from the locus of maximum traction forces, Fig. 4.16.

In each case the straight line approximation for the failure plane is that determined from Culmann's graphical solution for the earth pressure behind a retaining wall due to a surcharge load. For locations I, II and III it is clear that Culmann's solution is a valid method of determining the possible failure wedge in the case of a reinforced earth wall subject to a strip surcharge load.

Further away from the wall, the locus of maximum traction forces did not coincide with the Culmann line for the

load at location IV. The existence of the wall was of less significance in this case as this load location approached that of a load on a semi-infinite reinforced earth mass. In this instance it was observed that the gauges registering maximum values were closest to a straight vertical line below the central axis of the strip load, Fig.4.16. This straight line is the locus of maximum vertical stresses in a semi-infinite mass due to a surcharge strip load, which would be a more realistic interpretation of the locus of maximum traction forces observed for load location IV.

4.4 MAXIMUM TRACTION FORCE AS A FUNCTION OF DEPTH

In considering the failure of a reinforced earth retaining wall system by breakage of the strips, the effect of the load, its magnitude and location, on the value of the maximum traction force in the strips at different depths must be known. This experimental work has facilitated in describing the variation of maximum traction force with depth.

The general shape of this curve was consistent for all load locations, the tendency being as follows: the maximum traction force increased to a maximum value at some depth below the surface, and thereafter decreased, down to level 10.

Results for the distribution of maximum traction force with depth for load location I are presented in Fig.4.17. The maximum value in this case occurred at level 3. If these

figures are compared to those for load location II, Fig.4.18, two points are quite clear:

1. At all levels the maximum traction forces for load location I were greater than those for load location II, for the same surcharge loads.
2. The level at which the maximum stress occurred had moved down to level 4 for load location II, for all three surcharge load magnitudes.

Distribution for load location III are given in Fig.4.19. It is observed again that the values of maximum traction force for this load location, at all levels, were less than those for load location II, for the same surcharge loads.

Distributions for load location IV are given in Fig.4.20. Again the values of maximum traction force were less than those at corresponding levels for the same vertical surcharge load at location III.

From the above results it is clearly evident that the proximity of the strip load to the wall face plays a large role in determining the magnitude of the traction force in the strips. The closer the load is to the wall face, the greater the value of maximum traction force in the strips, for a given magnitude of surcharge load. Thus with respect to tensile failure of the reinforcement due to a strip load acting on the surface of the reinforced earth mass, load location I is the most critical (as evidenced by the highest

traction force recorded, see level 3, Fig.4.17). As the surcharge load moves away from the wall, the effect of the wall upon the traction force in the strip is reduced, until a point is reached beyond which, no further reduction in the traction force is possible. This point is the same point at which the load may be considered to act upon a semi-infinite reinforced earth mass.

4.5 BEHAVIOUR OF THE WALL FACE

The movement of the wall was monitored in all tests as it was felt that its deflection ought to reflect measurements of the traction force, and would shed light upon the deformation mechanism of the reinforced earth retaining wall under a strip loading. Results of the wall deformation are presented in Figs.4.21 to 4.28. Wall deflection readings are presented in tables 4.20 to 4.37. The deflected shape of the wall did indeed reflect the shape of the distribution of the maximum strip traction force with depth in the following ways:

1. It increased to a maximum at some depth below the sand surface (except for load location I where the outward deflection is a maximum in the uppermost channel), and thereafter reduced to a lower value at the bottom.
2. The outward deformation of the wall reduced at all levels as the surcharge strip load moved further away from the wall.

3. The outward deformation, at each location, was proportional to the magnitude of the surcharge strip load.

The lower portion of the wall deformed primarily as a result of strip elongation; the upper portion deformed as a result of the large pressure exerted thereon by the surcharge load. This is explained as follows:

From an average strain value for each strip it was possible to estimate the overall elongation of the strip. These values are presented in table 4.38. By comparing these values of strip elongation to the wall deformation at each level, the following observations and conclusions have been made:

- 1) At the lower levels, such as 8 and 10, the estimated values of strip elongation are close to, but in most cases just a little bit less than, the values of wall deformation. This indicates that most of the wall deformation takes place due to elongation of the strips. At level 10, 70 % of the wall deformation is a result of strip elongation, and at level 8 this figure is 66 %, (these are average values from the test results). The rest of the deformation at these levels may be attributed to a breakdown of the arching effect, discussed in section 2.3, (Fig.2.6). This is a shear failure of the sand between the strips, and occurs due to large stresses induced in the soil mass by the surcharge load.

2) At the upper levels, strip elongation is a much smaller contributing factor to the wall deformation, as may be seen from the large difference between the values in table 4.38, and those presented in Figs. 4.21 to 4.28. For instance, at level 4, on average, only 42 % of the wall deformation is due to the strip elongation, and at level 3 this figure is 36 %, (again these are average values from the test results). The rest of the movement in the upper portion of the wall is due to the breakdown of the arching effect. This effect is much greater in the upper portion of the wall, as in this region the stresses induced in the soil by the surcharge load are much higher, resulting in a more extensive breakdown. In addition, further confirmation of the dominant effect on the wall deflection played by the larger soil stresses in the upper levels, is that the deflection in this region for a given magnitude of the surcharge strip load is greatest when the surcharge load is at the wall face, and diminishes as the load moves further away from the wall.

4.6 EFFECT OF HORIZONTAL COMPONENT ON TRACTION FORCE DISTRIBUTION

The horizontal load was applied in two directions, towards and away from the wall. These two cases yielded significantly different results and will be treated separately.

4.6.1 Horizontal Component Directed Towards the Wall Face

The effect of this horizontal load component on the strip traction force for different strip levels and different load locations is illustrated in Figs. 4.29 to 4.34. It can be seen that an overall increase in the strip traction force at all levels and for all load locations occurred as a result. However, the most pronounced increases only occurred in the region close to the wall face. As can be seen from the figures, the region within which this significant increase occurred can be approximated to that of the active zone. The reason for this increase is that under a vertical load only, stresses in this active region transferred from the soil to the strip are directed towards the wall face, see Fig. 2.8. The horizontal load component applied on the soil surface in a direction towards the wall face causes stresses in the same direction to be transmitted to the strips. Thus a significant increase in the strip traction force will result.

Just behind the active zone, it can be seen from Figs. 4.29 to 4.34, that a decrease in the traction force occurred, due to the application of the surcharge load. This decrease was observed in all the tests, and at all the strip levels. The decrease occurred due to the fact that within the resistant zone, stresses transferred from the soil to the strip, under a vertical load only, are now directed away from the wall face, Fig. 2.8. The horizontal load component,

being directed towards the wall face, causes stresses in a direction towards the wall face to be transmitted to the strips from the soil. This then causes a decrease in the strip traction force, as evidenced in the region just beyond the active zone.

Further away from the wall, there was a smaller increase in the strip traction force with increases in the horizontal load, as can be seen from the figures. This may be explained by assuming that the traction force increase was an indirect result of the application of the horizontal load component, and only occurred in order to compensate for the increase in the traction force in that part of the strip within the active zone.

Another result of applying the horizontal load component was, in some instances, a shift in the position of maximum traction force along the strip to a point closer to the wall face, as may be seen in Figs. 4.32 and 4.33.

The above trends were observed in all the tests, and for each load location. The resulting stress distribution was a departure from the traction force distribution discussed in section 4.2. A more detailed analysis of the effects of the horizontal load component will be discussed later.

4.6.2 Horizontal Component Directed Away From the Wall Face

Directing the horizontal load component away from the wall face results in changes in the strip traction force as shown in Figs. 4.35 to 4.40. It can be seen that within the active wedge the traction force reduces in all cases upon application of the horizontal load. In order to explain this, one must refer back to Fig. 2.8, which shows the stresses transferred to the strips from the soil, under a vertical surcharge load, to be directed towards the wall face within the active zone. The application of the horizontal load component away from the wall face causes stresses in a like direction to be transmitted to the strips within the active wedge. This then causes a reduction in the strip traction force in this region.

It is clear from Figs. 4.35 to 4.40, and was apparent in varying degrees for each strip in all the tests with the load directed away from the wall face, that it is the maximum traction force value which decreases least of all with the application of the horizontal load increments. This can be explained as follows: Upon application of the vertical surcharge load a potential failure plane was formed within the reinforced earth mass. The failure plane is defined by the locus of maximum traction forces in the strips. Once the failure plane has been formed and stresses have been mobilized along it, (and these stresses result in the maximum traction forces in the strips), application of the horizon-

tal load component away from the wall was unable to have a restorative effect, on the failure plane and was therefore ineffective in reducing the stresses which result in the maximum traction forces. This effect was further confirmation of the formation of a potential failure plane.

It may be observed from the above figures, that within the resistant zone, beyond the potential failure plane, there is a reduction in the strip traction force, upon application of the horizontal load component. This may be explained by considering that within this region, under a vertical load only, the stresses mobilized on the strip surface are directed away from the wall face, Fig. 2.8. The effect of applying a horizontal load component to the sand surface, directed away from the wall face, was to introduce a lateral compressive stress to the reinforced earth system in the resistant zone. This compressive stress has the effect of reducing the required soil-strip stress transfer within this zone, hence the reduction in traction force. In all tests it was observed that this effect became less noticeable with depth, and below level 5 a small increase in the traction force was observed in the strips in the resistant zone.

4.7 EFFECT OF HORIZONTAL COMPONENT ON LOCATION OF THE FAILURE PLANE

Figs. 4.41 to 4.46 present a picture of the shift in the point of maximum traction force in the strips, from the situation under a vertical load only, to that with the full horizontal load component applied. As can be seen from the figures, the application of the horizontal load component resulted in a small shift of the point of maximum traction force at some levels; in each case the shift was in the same direction as the horizontal load component. Hence a small shift in the point of maximum traction force is likely to occur in the direction of, and proportional to the horizontal load component. However, the shift in the maximum was not always possible to pinpoint, especially for smaller values of the horizontal load component, as only a limited number of strain gauges were placed on each strip, for reasons mentioned in section 2.3.1.

4.8 EFFECT OF HORIZONTAL COMPONENT ON MAXIMUM STRIP TRACTION FORCES

The effect of the horizontal load component varies greatly between that directed towards, and that directed away from the wall face, and hence the two cases will be treated separately.

4.8.1 Horizontal Component Directed Towards the Wall Face

Figs. 4.47 to 4.49 show the effect of this load component on the maximum traction force values. It may be seen from the figures that an increase in the maximum traction force in every strip was noted with each increase in the horizontal load component. The rate of increase, as is evident from the figures, diminished as the load moved further away from the wall.

4.8.2 Horizontal Component Directed Away From the Wall Face

As mentioned and explained in section 4.6.2, it was the values of the maximum traction force which decreased least of all upon application of the horizontal component away from the wall face. The reason being that these maxima lie upon the potential failure plane. As a result, very little decrease was noted in the values of the maxima at all levels, as may be seen in Figs. 4.50 and 4.51.

Hence the values of maximum traction force may be considered not to be influenced at all by the application of a horizontal load component directed away from the wall. This is in marked contrast to the sensitivity of the maxima to a horizontal load component directed towards the wall face.

4.9 OVERALL CHANGE IN STRIP TRACTION FORCE DUE TO HORIZONTAL COMPONENT

As has been made clear from the preceeding sections, the effect of the horizontal load component on the strip traction forces was greatly different for the two opposing directions in which it was applied. Of further significance was the fact that although the horizontal load components were applied in opposite directions, the effect they had on the traction forces were not, in any way, the inverse of each other.

However it was noted, (see Figs. 4.52 and 4.53), that for both load directions, the relationship between the change in the strip traction force and the horizontal load component was virtually linear in most instances. Based on this observation, this relationship was assumed to be linear for simplicity of further analysis of the behaviour of the reinforced earth retaining wall system under a horizontally applied load component.

It was also noted, and is shown in Figs. 4.54 to 4.57, that this relationship between the change in strip traction force and the applied horizontal load component was independent of the magnitude of the vertical component of the load. That is to say, for both a vertical load of 60 KN/m^2 and 100 KN/m^2 , approximately the same change was brought about in the strip traction force by the same horizontal load component, for each value of the vertical load.

Hence the change in the strip traction force was interpreted in terms of the horizontal load component only, and not in terms of a resultant force vector.

Based upon the above reasoning and assumption, it is now possible to present a practicable analysis on the effect of the horizontal load component on the stress in the reinforcing strips. In the following discussion, strip traction force will be replaced by strip stress, in order to maintain consistency of the units, and so that the slope of the horizontal stress-strip stress relationship be non-dimensional.

The experimental data for this section is presented in terms of contours. The contours are of equal values of the slope of the horizontal stress-strip stress relationship and are thus dimensionless. The contours are plotted on a side view of the reinforced earth model, and were determined from the slopes of the horizontal stress-strip stress relationships for each strain gauge. The contours were plotted by computer, utilizing a plotter subroutine.

The contour diagrams give a very clear indication of the regions within the reinforced earth retaining wall system which are most sensitive to changes in the horizontal load component. Furthermore they also record the magnitude of the response of the strip stress to changes in the horizontal load component.

4.9.1 Horizontal Component Directed Towards the Wall Face

Figs. 4.58 to 4.63 present the contours for each load location wherein the horizontal component is directed towards the wall face.

The first point evident from looking at these contour diagrams is the fact that the value of the dimensionless contours is positive throughout the reinforced earth system, indicating a corresponding increase in the strip stress (in any point of any strip), with an increase in the horizontal load component at all of the load locations.

The region within which the most significant increase in the strip stress occurred may be closely approximated by the active zone, as defined in section 4.3. This approximation holds for load locations I, II, and III, and is illustrated by the dashed lines in Figs. 4.58 to 4.62.

As may be seen by comparing the maximum values of the contours for each load location, the greatest increase in the strip stress is brought about in the situation where the load is at the wall face, and then decreases as the load is positioned further away from the wall face. For the load at location I, Fig. 4.58, the largest values of the contours is 9,000, and this then decreases to a value of 2,000, for the load at location IV, Fig. 4.63. This trend was consistent throughout all the tests.

Hence the proximity of the load to the wall face has a direct effect on the sensitivity of the change in the existing strip stress to the applied horizontal load component.

Also visible from an overlook of the contour diagrams is the definite direction of the shift of the region of greatest sensitivity to the horizontal load component. When the load is at the wall face, this region is also at the wall face, Fig.4.58, but as the load is moved further away from the wall, Fig.4.60, the region has moved downwards from the surface, and also away from the wall face. This trend may be followed through Figs.4.61 and 4.62, (load location III), as the region moves further down and away from the wall, to the situation shown in Fig.4.63, where this region of maximum sensitivity is at its deepest point in the reinforced earth system, and furthest away from the wall face.

Hence this region may be seen to follow the position of the load, but always staying just aside of the load, in the direction in which the load is applied.

4.9.2 Horizontal Component Directed Away From the Wall Face

Contours for this loading direction, for all four load locations are presented in Figs.4.64 to 4.69.

Initially, it may be seen from these diagrams, that for the most part, the dimensionless contours have a negative value, corresponding to a decrease in the strip stress upon the application of a horizontal load component. There were two separate regions, however, where an increase in the strip stress was recorded:

1. In the region immediately under the load, a moderate increase in the strip stress was recorded in most tests, corresponding to an increase in the horizontal load component. Otherwise a much smaller negative value of the contours was recorded, as in Figs. 4.65 and 4.66. This effect was probably due to the localized effect of the load component.
2. In all tests, for all load locations, it was observed that in the lower right hand portion of the model there occurred an increase in the strip stress as a result of the horizontally applied load component. The rate of change of this increase in the strip stress is relatively small, being in the region from 0 to 1,000.

The larger changes in the strip stress with the load directed away from the wall face, were brought about when the load was closer to the wall face, and decreased as the load was positioned further away from the wall face.

As may be seen from all the figures, there are two separate areas within the reinforced earth medium wherein the rate of change, (in this case, decrease) of the strip stress with the applied horizontal load component has a local maximum.

The first is located in the active zone. It can be seen that for the load at the wall face, Figs. 4.64 and 4.65, this region is also at the wall face. As the load moves further

away from the wall face, this region of maximum sensitivity tends to move with it, as may be seen in Figs.4.66 through 4.68 to Fig.4.69. Parallel to the inward moving trend of this region is the increase in magnitude of its maximum contour value, from -4,000 where the load is at the wall face, to a value of -2,000 when the load is at location IV.

The second region is located in the resistant zone. As the load is positioned further away from the wall face this region moves with it, always staying aside of the load, in the direction in which the horizontal component is applied. Along with the lateral shift of this region is an increase in its value, from a value of -4,000 for the load at the wall face, Fig.4.64, through -3,000 for load location II, Fig.4.66, to a value of -2,000 for the load at location IV, Fig.4.69.

It is of relevance to note that these two regions may be roughly divided by the potential failure plane, (see dashed line in Figs.4.64 to 4.68). This is the line along which, as discussed in section 4.6.2, the smallest decrease occurs under a horizontal load component being directed away from the wall face, and is due to the formation of a potential failure plane.

4.10 EFFECT OF HORIZONTAL COMPONENT ON BEHAVIOUR OF WALL FACE

Figs. 4.70 to 4.77 present the wall deformation under the vertical load and an increasing horizontal load, for the horizontal load component directed both towards and away from the wall, for all four load locations.

The case with the horizontal load component directed towards the wall face is presented in the first four figures. The greatest increase in the wall deflection occurs when the load is at the wall face, Fig.4.70, as can be seen from the large deflections, especially in the upper half of the wall, for a horizontal load component of 10 KN/m^2 . For the load at location II, Fig.4.71, the deflection at all levels has reduced, despite the larger horizontal load components up to 26 KN/m^2 . The amount of deflection further reduces for the load at location III, Fig.4.72, to those for load location IV, Fig.4.20. It should also be noted, as is evident from the diagrams, that although the horizontal load component increases in constant intervals, the wall deflection increases in ever-increasing intervals. So, any further deflection of the wall due to the horizontal load component directed towards the wall face is dependent on two parameters:

1. The magnitude of the horizontal load component, and
2. The proximity of the load to the wall face.

This latter parameter, and the magnitude of any existing horizontal component determine the sensitivity of the wall deflection to the horizontal load component.

The greatest deflection, in all cases, occurs in the uppermost channel section, and decreases to a minimum at the base of the wall. Again, the larger deflections, especially in the uppermost strips, may be attributed to the partial breakdown of the arching effect in this region due to the high stresses induced in the soil mass by the horizontal load component directed towards the wall face.

Figs. 4.74 to 4.77 show how the wall deflects when the horizontal load component is directed away from the wall face. As can be seen, the greatest change in deformation occurs in the uppermost channel section, and decreases to zero at around level 7.

Again, when the load is closer to the wall face, at load locations I and II, the wall deflection is more sensitive to changes in the horizontal load component, Figs. 4.74 and 4.75, and becomes less so as the load is positioned further away from the wall face, as can be seen from Figs. 4.76 and 4.77, for load locations III and IV. It can also be seen that in the two uppermost strips, the deflection increases in ever-increasing intervals.

The negative readings, realized in some instances when the load is directed away from the wall face, can be attributed to an overall deformation of the combined system of soil, strips and facing elements under the applied loading.

Chapter V

INTERPRETATION OF RESULTS

5.1 MOBILIZED SOIL-STRIP FRICTION

In order to make an estimate of the degree of soil-strip friction mobilized at each reinforcement level, certain assumptions must be made as to the state of stress within the reinforced earth system. These assumptions are illustrated in Fig.5.1, and are:

1. The vertical stress within the reinforced earth mass due to the surcharge load is distributed according to the 2:1 dispersion lines convention. Within this region the vertical stress varies only with depth. Outside it the vertical stress is zero.
2. There is a linear boundary between the active and resistant zones. This boundary is the straight line joining the base of the wall to the inside edge of the strip load.

If the portion of the reinforcing strip which lies both in the resistant zone and within the 2:1 dispersion lines is considered as a free-body, Fig.5.2, from a consideration of static equilibrium, the shear stresses, τ , acting along it in the direction away from the wall must equal the maximum traction force, $T_{\max}$, which acts at the boundary between the

active and passive zones. The force equilibrium equation for this free-body is:

$$T_{\max} = \sigma_v \cdot 2b \cdot \Delta l \cdot f \quad \dots 5.1$$

where f is the actual coefficient of friction mobilized between the soil and the strip. This coefficient of friction must always be less than or equal to a maximum value of $\tan 40^\circ = 0.84$, (this maximum value is the internal friction angle of the sand used in the experimental work), as sand had been glued to the strips. If the coefficient of friction is greater, slippage of the strips within the sand would have occurred.

Every term in the above equation, except f , may be determined at each level: σ_v and Δl from the above two assumptions, and $T_{\max}$ from the experimental results. This enables a value of f to be determined at every level. Figs. 5.3 to 5.6 plot the values of f , calculated from the above equation, as a function of depth, for the load at locations I to IV respectively. The values of the friction coefficient are presented in Table 5.1.

As mentioned, the maximum value of f is 0.84. This value is exceeded at levels 2 and 3 when the load is at location I. This indicates that slippage has occurred between the soil and the strip at these levels. From level 4 down, the friction between the soil and the strips decreases continuously.

For the load at location II, the value of friction mobilized increases to a maximum value of 0.76 at level 3, Fig. 5.4, and decreases thereafter with depth.

For load locations III and IV, Figs. 5.5 and 5.6, the values of f determined at each strip level are less for load location IV than those determined for load location III.

The values of f determined in the above manner are proportional to the measured values of T_{max} . If the density of reinforcing strips were greater, the measured values of T_{max} would be smaller, and accordingly, the values of f . However the results shown in the figures also indicate the trend of the mobilized soil-strip friction, which will be the same irrespective of strip density.

It is evident from a consideration of the above information that under a surcharge strip load, the region close to the surface of the reinforced earth medium is the region wherein failure of the system by lack of adherence between the soil and the reinforcing strips is most likely to occur.

However, when the load is at the wall face it is the very uppermost strips which are likely to slip; due to concentration of stresses in this region.

Further down from the surface, the friction mobilized reduces, and this aspect of the design becomes less critical; now the self weight of the soil becomes the governing design factor.

5.2 MAXIMUM TRACTION FORCE AS A FUNCTION OF DEPTH

An estimation of the maximum traction force in a reinforcing strip is given by Kennedy et al., (16). This is a modification of Terzaghi's formula for the computation of the lateral pressure against a conventional rigid retaining wall:

$$T_{max} = (2-R) \cdot q \cdot (\beta - \sin[\beta] \cdot \cos[2\alpha]) / \pi \quad \dots 5.2$$

where q is the strip load, α , and β , as defined in Fig. 2.10, and R is reduction factor based upon the stiffness characteristics of the backfill material and the strips:

$$R = \frac{A \cdot E_{t \text{ backfill}}}{A \cdot E_{t \text{ backfill}} + A \cdot E_{t \text{ strips}}} \quad \dots 5.3$$

where $E_{t \text{ backfill}}$ is the tangent modulus of the backfill. Duncan and Chang(3), give an expression for this tangent modulus:

$$E_t = \left[1 - \frac{R_f \cdot (1 - \sin\phi) \cdot (\sigma_1 - \sigma_3)}{2 \cdot c \cdot \cos\phi + 2 \cdot \sigma_3 \cdot \sin\phi} \right]^2 \cdot K' \cdot P_a \left[\frac{\sigma_3}{P_a} \right]^n \quad \dots 5.4$$

where σ_1 and σ_3 are the major and minor principle stresses respectively; R is the failure ratio:

$$R = ([\sigma_1 - \sigma_3] \text{ at Failure}) / (\text{asymptotic value of } [\sigma_1 - \sigma_3]) \dots 5.5$$

K is a modulus number; n is an exponent determining the rate of variation of the initial tangent modulus with σ_3 ; P_a is atmospheric pressure; ϕ is internal soil friction, and c is soil cohesion.

Kennedy et al. replaced σ_1 and σ_3 with σ_v and σ_h , the vertical and horizontal stresses due to the surcharge strip load and weight of the soil soil backfill:

$$E_t = \left[1 - \frac{R_f \cdot (1 - \sin\phi) \cdot (\sigma_v - \sigma_h)}{2 \cdot c \cdot \cos\phi + 2 \cdot \sigma_h \cdot \sin\phi} \right]^2 \cdot K' \cdot P_a \left[\frac{\sigma_h}{P_a} \right]^n \quad \dots 5.6$$

and use this expression to calculate a value for the tangent modulus of the soil backfill. However in doing so the authors use values of σ_v and σ_h which correspond to given loading conditions on the reinforced earth medium (i.e. the soil backfill with the reinforcing strips). The value obtained for E_t consequently is not the tangent modulus of the soil backfill alone as stated in equation 5.3, rather it is representative of the combined media, and as such is incorrectly used in equation 5.3, which is based upon the different stiffness characteristics of the combined media.

Furthermore, by using these values of σ_v and σ_h in equation 5.5, the term

$$(R_f \cdot (1 - \sin\phi) \cdot (\sigma_v - \sigma_h)) / (2 \cdot c \cdot \cos\phi + 2 \cdot \sigma_h \cdot \sin\phi)$$

can often be greater than unity. However, the maximum possible value of this term is unity, as it is the ratio of the

existing value of $(\sigma_v - \sigma_h)$ in the soil to the asymptotic value of $(\sigma_v - \sigma_h)$, and failure will have taken place if it is ≥ 1 . The authors state that if this term ≥ 1 , then E_s is to be taken as zero.

Following the above premise, R will be equal to zero under certain loading conditions, and this will cause discontinuities in the distribution of maximum traction forces with depth. These discontinuities can be seen in Figs. 5.7 to 5.10, which present values of T_{max} calculated from equation 5.2, for the different loads and different load locations. Values of R , K' , n , c and ϕ for a cohesionless backfill are taken from Al-Hussaini and Johnson(2), and are: $R_f = 0.85$; $K' = 580$; $n = 0.5$; for $c = 0$, and $\phi = 30^\circ$.

Furthermore, a comparison may be made between these graphs and the actual measured values of the maximum traction force as a function of depth.

Fig. 5.11 shows experimentally measured values of T_{max} on a graph of the values of T_{max} , calculated from equation 5.2, for load location I. Figs. 5.12 to 5.14 present measured and calculated values for the load at locations II, III and IV respectively.

It can clearly be seen from these comparisons, that the closest correspondence between the experimental and theoretical results occurs for the load at location IV. As the load is positioned closer to the wall face the difference between the theoretical and experimental results becomes much larger.

The discontinuities in the value of R , which are manifest in the irregular distribution of T_{max} with depth, are one of the two factors causing the discrepancy between the theoretical and experimental results. The second factor is the sensitivity of equation 5.2 to the value of d , the distance from the load to the wall face, Fig.2.11. For small values of d , T_{max} is much greater than the experimental values in the upper part of the reinforced earth system, and then reduces to a value smaller than the experimental values as the depth increases. Then for larger values of d , the difference between the experimental and theoretical values diminishes to that shown in Fig.5.14.

It can be seen from Figs.5.7 to 5.10 that the discontinuities in the theoretical values of T_{max} are greatest for the load at the wall face, and diminish as the load is positioned further away from the wall face.

Hence it may be concluded, that the above method given by Kennedy et al. for the estimation of the maximum traction force in the reinforcing strips has good agreement with the experimental values when the load is distant from the wall face; but at distances close to the wall face, the theoretical values are over-conservative in the upper region of the system, and underestimate the experimental values in the lower region.

5.3 STRESS DISTRIBUTION DUE TO HORIZONTAL LOAD COMPONENT

The stress distribution occurring in the soil backfill due to the horizontal load component may be deduced from the horizontal load component-strip stress contours. This is achieved by considering a unit element of the reinforced earth medium, Fig.5.15, under an additional lateral stress $\Delta\sigma_w$, acting on the plane ABCD; assuming that this extra lateral stress is taken up by the reinforcing strip, then the following equation of equilibrium may be written:

$$\Delta\sigma_w \cdot ds \cdot dh = \Delta\sigma_s \cdot A \quad \dots 5.6$$

where $\Delta\sigma_s$ is the additional strip stress, and A is the cross-sectional area of the reinforcing strip. Dividing both sides of the above equation by H , the increment of the horizontal load component, gives:

$$\frac{\Delta\sigma_w}{\Delta H} \cdot ds \cdot dh = \frac{\Delta\sigma_s}{\Delta H} \cdot A \quad \dots 5.7$$

which can be written as:

$$\frac{\Delta\sigma_w}{\Delta H} = \frac{A}{ds \cdot dh} \cdot \frac{\Delta\sigma_s}{\Delta H} \quad \dots 5.8$$

where $(\Delta\sigma_s / \Delta H)$ is the ratio of change in strip stress to change in the horizontal load component, presented in Figs.4.54 to 4.65. $(\Delta\sigma_w / \Delta H)$ is the ratio of the change in the soil stress to the change in the horizontal load component. Contours of these values are presented in Figs.5.16 to 5.18, for the load component directed towards the wall face.

The type of stress distribution proposed by the French Ministry of Transport(20), which is used for design purposes, is shown in Fig.2.11. Their approach proposes an additional horizontal stress component acting at right angles on a vertical plane through the centre of the loaded area. The maximum additional stress occurs at the surface, and decreases linearly to zero at a depth h , which is given only as a function of ϕ , the angle of internal soil friction. This stress distribution is assumed to occur only along the vertical plane through the centre of the loaded area.

Figs.5.19 to 5.21 show the stress distribution along this plane, as taken from the contours of Figs.5.16 to 5.18. As can be seen this distribution has its maximum value below the surface, the depth of which is proportional to the distance of the load from the wall face. It may also be seen from Figs.5.16 to 5.18 that the region of greatest sensitivity to the horizontal load component lies somewhat to the side of the centreline of the loaded region, in the direction in which the horizontal component is directed. Thus the French Ministry of Transport err in assuming that the maximum additional stress due to the horizontal load component occurs immediately under the centre of the loaded area.

Poulos and Davis(22), give the following expression for the horizontal stress induced in a semi-infinite elastic medium under an infinite horizontal strip load, Fig.5.24:

$$\sigma_h = (H/\pi) \cdot \left(\ln \frac{R_1^2}{R_2^2} - \sin \alpha \cdot \sin(\alpha + 2\delta) \right) \quad \dots 5.9$$

The solution for this equation is presented in dimensionless form in Fig. 5.25. It can be seen that the maximum stress occurs immediately under the edge of the loaded area. This distribution is in closer agreement to the observed results than the French approach. However it still assumes that the maximum stress occurs at the surface. The reason for the maximum not occurring close to or at the surface in the experimental work may be justified by the fact that the load acts very close to a boundary, the wall face, (not accounted for in equation 5.9 above). The relatively large deflections in the upper part of the wall, (see Figs. 4.66 to 4.68), have the effect of relaxing the large stresses induced by the horizontal load component in this region, hence the maximum value occurs not at the surface, but at a certain depth below the surface.

Furthermore, the French approach does not consider the case where the horizontal load component is directed away from the wall face. Contours for this situation are presented in Figs. 5.22 and 5.23. In this case there are two separate regions within the reinforced earth mass which are sensitive to the horizontal load component, one at a certain depth below the load itself, and another to the side of the load, in the direction in which the load is directed.

The above contour diagrams may thus be used in calculating the additional stresses induced in the reinforcing strips due to a horizontal load component on any reinforced

earth retaining wall system, as they are independent of the cross-sectional area of the strips, and the density of the strips within the granular backfill.

5

Chapter VI

CONCLUSIONS AND RECCMMENDATIONS

6.1 CONCLUSIONS

Based on the experimental and analytical work presented in this thesis, the following conclusions may be made:

1) Under vertical loading conditions only, and for any given magnitude of vertical load, the most critical load/position observed was that at the wall face, i.e. at this position, the largest stresses in the strips and the largest deformation of the wall were obtained.

2) Culmann's graphical method for determining the position of the failure plane has close agreement with the experimentally observed plane, for loads within the $45^\circ + \phi/2$ Rankine active wedge. Outside this region, Culmann's solution is not representative of the observed results.

3) Measurements of the wall deformation allowed a simple determination of the degree to which the breakdown in the arching effect occurred under the strip loading surcharge. The extent of this effect was in direct proportion to the stress induced in the reinforced earth mass by the surcharge load.

4) The change in the strip stress due to the horizontal load component may be assumed to be independent of the mag-

nitude of the existing vertical component. This has been verified for magnitudes of the horizontal component up to one third of the vertical component.

5) A horizontal load component directed towards the wall face has the effect of decreasing the factor of safety with respect to tensile failure of the reinforcement.

6) A horizontal load component directed away from the wall face has an overall effect of decreasing the strip traction force; except the values of maximum traction force, which are not significantly affected by the application of the horizontal load component away from the wall face.

7) The upper region of the reinforced earth retaining wall most fully mobilizes the coefficient of soil-strip friction. Hence it is the most critical region with respect to failure due to soil-strip slippage under the effect of a surcharge strip load. At greater depths the self weight of the backfill soil mass takes over as being the more important factor in design considerations.

8) The method proposed by Kennedy et al. (10) for the distribution of maximum traction forces under a vertical load only, has good agreement with the experimental results only when the load is located outside the region defined by the $45^\circ + \phi/2$ Rankine active wedge. At distances closer to the wall face, the proposed distribution of maximum traction forces with depth departs increasingly from the observed values, being over-conservative in the upper region, and underestimating the observed values in the lower region.

9) Upon application of the horizontal load component, both towards and away from the wall face, the region of the reinforced earth mass in which the greatest change in strip stress occurred, was located at a depth of approximately one third of the wall height below the surface, and aside of the load itself, in the direction in which the load was directed.

6.2 RECOMMENDATIONS FOR FURTHER RESEARCH

1) Pressure cells could be placed within the reinforced earth mass to determine the horizontal and vertical soil stresses. This would shed light upon the assumption used to determine the soil stress distribution from the strip traction force.

2) It would be helpful to determine the the traction force distribution due to a vertical surcharge load on a semi-infinite reinforced earth mass with the same properties and strip density as used in the model. This data could then be compared to the distributions obtained in the retaining wall model to determine more specifically the effect of the proximity of the load to the wall face on the mobilized strip traction force.

3) Photoelastic studies of a load positioned near the edge of a finite elastic medium (representing a load near the edge of a reinforced earth retaining wall), would shed light upon the stress distribution due to a vertical and a horizontal load.

- 4) It would be worthwhile to perform similar load tests on a model wall, but with varying strip footing widths, in order to establish the effect on the strip traction force, especially with respect to a horizontal load component.
- 5) The effect of a repetitive or alternating horizontal load component is worth investigating, as this type of loading is likely to occur when the reinforced earth retaining wall is used as a bridge abutment.

APPENDIX I

FIGURES

Fig. 2.1 Elementary Cube of Unreinforced Earth.

Fig. 2.2 Mohr's Circle of Stress, and Failure Envelope for the Soil.

Fig. 2.3 Elementary Cube with Reinforcement.

Fig. 2.4 Rigid, Non-moving, Retaining Wall, Supporting Granular Backfill in the At-rest condition.

Fig. 2.5 Soil Mass Reinforced with Reinforcing Strips.

Fig. 2.6 Schematic View of the Arching Effect, Between the Strips.

Fig. 2.7 External Loads on the Reinforced Earth Retaining Wall.

Fig. 2.8 Stresses Exerted on the Reinforcement by the Soil.

Fig. 2.9 Distribution of Vertical Stress due to Surcharge Load.

Fig. 2.10 Distribution of Horizontal Stresses Against a Rigid, Vertical Retaining Wall due to a Surcharge Load.

Fig. 2.11 French Proposal for Distribution of Horizontal Stresses within Soil Mass due to a Horizontal Surcharge Load.

Fig. 2.12 Effective Length of the Reinforcement.

Figs. 2.13 and 2.14 Design Values of Friction and Coefficient of Lateral Earth Pressure as a Function of Depth.

Fig. 2.15 The Use of Beams in Containing Excessive Lateral Stresses Developed at the Base of Embankments.

Fig. 3.1 Side Elevation of Containment Box and Reinforced Earth Retaining Wall.

Fig. 3.2 Grain Size Distribution Curve for the Sand Backfill.

Fig. 3.3 Results of a Shear Box Test on the Sand Backfill.

Fig. 3.4 Results of a Stress-Strain Test on a Reinforcing Strip, Instrumented with Strain Gauges.

Fig. 3.5 Vertical Section Through the Skin Elements and Reinforcing Strips.

Fig. 3.6 View in Plan of the Skin Elements and Reinforcing Strips.

Scale 1:5

Fig. 3.7 Location of the Strain Gauges on the Reinforcing Strips, scale is 1:5.

Fig. 3.8 Electronic Strain Gauge Indicator.

Fig. 3.9 Dial Gauges Used to Read Wall Deflection.

Fig. 3.10 Building up the Reinforced Earth System.

Fig. 3.11 Schematic View of Leverage System Used to Load the Reinforced Earth Retaining Wall.

Fig. 3.12 Loading System : Horizontal Component Directed Towards the Wall Face.

Fig. 3.13 Loading System : Horizontal Component Directed Away From the Wall Face.

Fig. 3.14 Loading Block and Beam.

Fig. 3.15 Locations of the Surcharge Load.

Fig. 4:1- Boussinesq's Stress Distribution and Approximated Stress Distribution.

Test no. 1

Horizontal Scale 1:5

Load Location I

Vertical Scale 1:3

$q = 60 \text{ N/m}^2$

Fig. 4.2 Traction Force Distribution Along Strips, Under Vertical Load.

Test no. 3

Horizontal Scale 1:5

Load Location I

Vertical Scale 1:3

$q = 80 \text{ N/m}^2$

Fig. 4.3 Traction Force Distribution Along Strips, Under Vertical Load.

Test no.6

Horizontal Scale 1:5

Load Location II

Vertical Scale 1:3

$q = 60 \text{ N/m}^2$

Fig. 4.4 Traction Force Distribution Along Strips, Under Vertical Load.

Test no. 7

Horizontal Scale 1:5

Load Location II

Vertical Scale 1:3

$q = 80 \text{ N/m}^2$

Fig. 4.5 Traction Force Distribution Along Strips, Under Vertical Load.

Test no. 8

Horizontal Scale 1:5

Load Location II

Vertical Scale 1:3

$q = 80 \text{ N/m}^2$

Fig. 4.6 Traction Force Distribution Along Strips, Under Vertical Load.

0 150 300
Traction Force (N)

Test no. 9

Horizontal Scale 1:5

Load Location II

Vertical Scale 1:3

$q = 100 \text{ N/m}^2$

Fig. 4.7 Traction Force Distribution Along Strips, Under Vertical Load.

Test no. 10

Horizontal Scale 1:5

Load Location II

Vertical Scale 1:3

 $q = 100 \text{ N/m}^2$

Fig. 4.8 Traction Force Distribution Along Strips, Under Vertical load.

Test no.12

Horizontal Scale 1:5

Load Location III

Vertical Scale 1:3

 $q = 60 \text{ N/m}^2$

Fig. 4.9 Traction Force Distribution Along Strips, Under Vertical Load.

Test no. 14

Horizontal Scale 1:5

Load Location III

Vertical Scale 1:3

 $q = 100 \text{ N/m}^2$

Fig. 4.10 Traction Force Distribution Along Strips, Under Vertical Load.

Test no. 17

Horizontal Scale 1:5

Load Location IV

Vertical Scale 1:3

$q = 60 \text{ N/m}^2$

Fig. 4.11 Traction Force Distribution Along Strips, Under Vertical Load.

Test no. 19

Horizontal Scale 1:5

Load Location IV

Vertical Scale 1:3

$q = 100 \text{ N/m}^2$

Fig. 4.12 Traction Force Distribution Along Strips, Under Vertical Load.

Fig. 4.13 Location of Potential Failure Plane.

Fig. 4.14 Location of Potential Failure Plane.

Load Location III

112

Test nos. 12,13,14

Fig. 4.15 Location of Potential Failure Plane.

Load Location IV

Test nos. 16,18,19

Fig. 4.16 Location of Maximum Traction Forces.

Fig. 4.17 Distribution of Maximum Strip Traction Force with Depth.

Fig. 4.18 Distribution of Maximum Strip Traction Force with Depth.

Fig. 4.19 Distribution of Maximum Strip Traction Force with Depth.

Fig. 4.20 Distribution of Maximum Strip Traction Force with Depth.

Figs. 4.21 and 4.22 Wall Deformation Under a Vertical Load at Load Location I.

Figs. 4.23 and 4.24 Wall Deformation Under a Vertical Load at Load Location II.

Figs. 4.25 and 4.26 Wall Deformation Under a Vertical Load at Location III.

Figs. 4.27 and 4.28 Wall Deformation Under a Vertical Load at Load Location IV.

Fig. 4.29 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.30 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.31 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.32 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.33 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.34 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.35 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.36 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.37 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.38 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.39 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.40 Change in Strip Traction Force due to Horizontal Load Component.

Fig. 4.41 Shift in Position of Maximum Traction Forces.

Fig. 4.42 Shift in Position of Maximum Traction Forces.

Fig. 4.43 Shift in Position of Maximum Traction Force.

Fig. 4.44 Shift in Position of Maximum Traction Force.

Fig. 4.45 Shift in Position of Maximum Traction Force.

Fig. 4.46 Shift in Position of Maximum Traction Force.

Fig. 4.47 Effect of Horizontal Component on Distribution of Maximum Strip Traction Force with Depth.

Fig. 4.48 Effect of Horizontal Component on Distribution of Maximum Strip Traction Force with Depth.

Fig. 4.49 Effect of Horizontal Component on Distribution of Maximum Strip Traction Force with Depth.

Fig. 4.50 Effect of Horizontal Component on Distribution of Maximum Traction Force with Depth.

Fig. 4.51 Effect of Horizontal Component on Distribution of Maximum Traction Force with Depth.

Fig. 4.52 Relationship Between the Change in Strip Stress and the Horizontal Load Component, for the Load Directed Towards the wall Face.

Fig. 4.53 Relationship Between the Change in Strip Stress and the Horizontal Load Component, for the Load Directed Away From the Wall Face.

Fig. 4.54 Change in Strip Stress as a Function of Horizontal Load Component, for Different Values of Vertical Surcharge Load.

Fig. 4.55 Change in Strip Stress as a Function of Horizontal Load Component, for Different Values of Vertical Surcharge Load.

Fig. 4.56 Change in Strip Stress as a Function of Horizontal Load Component, for Different Values of Vertical Surcharge Load.

Fig. 4.57 Change in Strip Stress as a Function of Horizontal Load Component, for Different Values of Vertical Surcharge Load.

Gauge no. Contour Value

1	3777
2	2730
3	449
4	93
5	5432
6	4992
7	2565
8	335
9	779
10	5998
11	4357
12	1102
13	1053
14	787
15	1117
16	7377
17	4321
18	695
19	490
20	80
21	1103
22	7525
23	4008
24	4925
25	1347
26	2142
27	982
28	9638
29	7405
30	2480
31	2751
32	2413
33	945
34	7322
35	3747
36	163
37	659
38	84
39	172

Fig. 4.58 Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Gauge no. Contour Value

1	3308
2	2818
3	460
4	82
5	5264
6	5308
7	3390
8	33
9	10
10	4282
11	4616
12	4068
13	1388
14	108
15	800
16	5202
17	5804
18	6406
19	1278
20	820
21	887
22	6495
23	9013
24	5387
25	1328
26	125
27	341
28	6349
29	8857
30	3122
31	446
32	1512
33	918
34	722
35	1828
36	126
37	263
38	972
39	382

Fig. 4.59 Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Gauge no. Contour Value

1	2972
2	2281
3	89
4	247
5	4432
6	4386
7	2827
8	123
9	702
10	4076
11	3918
12	3397
13	532
14	951
15	311
16	5019
17	5266
18	3812
19	458
20	364
21	270
22	5712
23	4834
24	3955
25	770
26	195
27	138
28	5456
29	6933
30	2712
31	190
32	1215
33	168
34	602
35	672
36	515
37	165
38	3
39	53

Test no.11
Load Location II

Side Elevation of Model scale 1:5

Fig. 4.60 Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Gauge no. Contour Value

1	1679
2	2046
3	483
4	33
5	3185
6	3671
7	3401
8	1019
9	715
10	3360
11	3886
12	4617
13	3557
14	3725
15	902
16	2323
17	4096
18	5869
19	3161
20	958
21	695
22	4215
23	6007
24	6309
25	2213
26	320
27	90
28	2009
29	3651
30	5676
31	681
32	846
33	880
34	164
35	1002
36	4304
37	202
38	711
39	202

144

Test no.13
Load Location III

Side Elevation of Model scale 1:5

Fig. 4.61. Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Gauge no. Contour Value

1	843
2	1317
3	179
4	15
5	2107
6	2883
7	2782
8	672
9	24
10	2222
11	3344
12	4202
13	3664
14	408
15	222
16	4576
17	4652
18	7428
19	4264
20	661
21	862
22	3961
23	5236
24	6228
25	1901
26	840
27	542
28	2345
29	3365
30	5624
31	1319
32	681
33	792
34	161
35	1045
36	3507
37	654
38	621
39	410

Fig. 4.62 Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Fig. 4.63 Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Gauge no. Contour Value

1	-854
2	-137
3	514
4	0
5	-1352
6	-864
7	-471
8	939
9	83
10	-1263
11	-1234
12	-1007
13	1454
14	86
15	-549
16	-3802
17	-2131
18	-782
19	294
20	323
21	-939
22	-4461
23	-2548
24	-634
25	-2030
26	-2502
27	-1714
28	-4272
29	-3543
30	-4182
31	-3972
32	-3467
33	-2050
34	-2729
35	1356
36	-571
37	-532
38	-2501
39	-781

Test no.1

Load Location I

Side Elevation of Model scale 1:5

Fig. 4.64 Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Gauge no. Contour Value

1	-1077
2	-761
3	438
4	296
5	-1400
6	-1399
7	-931
8	752
9	361
10	-2166
11	-2129
12	-2003
13	-451
14	453
15	-53
16	-2406
17	-3009
18	-2768
19	-498
20	-379
21	-585
22	-3772
23	-4501
24	-4109
25	-1011
26	-2428
27	-1854
28	-2392
29	-3576
30	-3353
31	-2508
32	-3034
33	-2518
34	741
35	499
36	4199
37	338
38	261
39

Fig. 4.65 Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Gauge no. Contour Value

1	-1202
2	-608
3	641
4	396
5	-2217
6	-1858
7	-1086
8	777
9	461
10	-2372
11	-2651
12	-2531
13	-450
14	275
15	329
16	-3819
17	-4092
18	-3419
19	-371
20	-645
21	901
22	-3678
23	-4386
24	-3898
25	-2537
26	-2528
27	-2209
28	-1344
29	-2448
30	-1896
31	-3187
32	-3432
33	-2886
34	15
35	2373
36	3279
37	2304
38	-1933
39	300

Fig. 4.66 Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Gauge no. Contour Value

1	-393
2	-246
3	252
4	210
5	-656
6	-717
7	-421
8	484
9	301
10	-1162
11	-1742
12	-1928
13	-1025
14	451
15	-26
16	-1230
17	-1959
18	-2688
19	-1214
20	209
21	-396
22	-1266
23	-2161
24	-3105
25	-1412
26	-692
27	-1077
28	-752
29	-1110
30	-3469
31	-857
32	-2415
33	-2550
34	-173
35	-369
36	-1003
37	-632
38	-2600
39	-1580

Fig. 4.67 Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Gauge no. Contour Value

1	-624
2	-444
3	243
4	224
5	-958
6	-1221
7	-671
8	602
9	194
10	-1493
11	-1940
12	-2054
13	-755
14	838
15	-184
16	-1449
17	-2235
18	-3020
19	-922
20	480
21	-523
22	-1485
23	-2034
24	-3017
25	-813
26	-1373
27	-1403
28	-673
29	-1239
30	-3288
31	214
32	-2958
33	-2369
34	14
35	132
36	-192
37	31
38	-1359
39	-732

Fig. 4.68 Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Gauge no. Contour Value

1	-505
2	-714
3	-194
4	599
5	-636
6	-983
7	-825
8	-335
9	886
10	-232
11	-587
12	-1087
13	-1730
14	-634
15	384
16	-681
17	-1172
18	-1818
19	-2520
20	-466
21	-34
22	21
23	-340
24	-1177
25	-2554
26	-418
27	-1070
28	453
29	353
30	-154
31	-1866
32	959
33	-2636
34	-328
35	-426
36	-502
37	-857
38	322
39	-1028

Fig. 4.69 Contour Diagram of Ratio of Change in Strip Stress to Horizontal Load Component.

Fig. 4.70 Wall Deformation Under Vertical and Horizontal Load Components at Location I.

Fig. 4.71 Wall Deformation Under Vertical and Horizontal Load Components at Location II.

Figs. 4.72 and 4.73 Wall Deformation Under Vertical and Horizontal Load Components at Locations III and IV.

Fig. 4.74 Wall Deformation Under Vertical and Horizontal Load Components at Location I.

Fig. 4.75 Wall Deformation Under Vertical and Horizontal Load Components at Location II.

Figs. 4.76 and 4.77 Wall Deformation Under Vertical and Horizontal Load Components at Locations III and IV.

Fig. 5.1 Partition of the Active and Resistant Zones, and the 2:1 Load Dispersion Configuration.

Fig. 5.2 Free-Body Diagram of Strip Portion.

Fig. 5.3 Coefficient of Mobilized Soil-Strip Friction, as a Function of Depth: Load Location I.

Fig. 5.4 Coefficient of Mobilized Soil-Strip Friction, as a Function of Depth: Load Location II.

Fig. 5.5 Coefficient of Mobilized Soil-Strip Friction, as a Function of Depth: Load Location III.

Fig. 5.6 Coefficient of Mobilized Soil-Strip Friction as a Function of Depth: Load Location IV.

Fig. 5.7 Distribution of T_{max} (theroetical), as a Function of Depth.

Fig. 5.8 Distribution of T_{max} (theoretical), as a Function of Depth.

Fig. 5.9 Distribution of T_{max} (theoretical), as a Function of Depth.

Fig. 5.10 Distribution of $T_{\max}$ (theoretical), as a Function of Depth.

Fig. 5.11 Comparison Between Experimental and Theoretical Values of T_{max} .

Fig. 5.12 Comparison Between Experimental and Theoretical Values of T_{max} .

Fig. 5.13 Comparison Between Experimental and Theoretical Values of T_{max} .

Fig. 5.14 Comparison Between Experimental and Theoretical Values of $T_{\max}$.

Fig. 5.15 Unit Cube of Reinforced Earth Acted upon by an Additional Lateral Stress.

Test no. 2
Load Location I

Side Elevation of Model Scale 1:5

Fig. 5.16 Contour Diagram of Ratio of Horizontal Soil Stress to Surcharge Stress, (experimentally obtained).

Test no. 8

Load Location II

Wall Face

Side Elevation of Model Scale 1:5

Fig. 5.17 Contour Diagram of Ratio of Horizontal Soil Stress to Surcharge Stress, (experimentally obtained).

Test no. 11

Load Location II

Fig. 5.18 Contour Diagram of Ratio of Horizontal Soil Stress to Surcharge Stress, (experimentally obtained).

Figs. 5.19, 5.20, 5.21 Values of the Ratio of Horizontal Soil Stress to Surcharge Stress Along the Centreline Through the Strip Load.

Wall Face

Test no. 1

Load Location I

Side Elevation of Model Scale 1:5

Fig. 5.22 Contour Diagram of Ratio of Horizontal Soil Stress to Surcharge Stress, (experimentally obtained).

Test no.12
Load Location III

Side Elevation of Model Scale 1:5

Fig. 5.23 Contour Diagram of Ratio of Horizontal Soil Stress to Surcharge Stress, (experimentally obtained).

Fig. 5.24 Infinite Horizontal Strip Load on Semi-Infinite Elastic Medium.

Contours of the Horizontal Soil Stress:Surcharge Stress Ratio

Fig. 5.25 Dimensionless Solution to Equation 5.9.

APPENDIX II

TABLES

Table 3.1 Loading Schedule for Experimental Programme

Test No.	Load Location	Load Components		Direction
		Vertical $q, \text{KN/m}^2$	Horizontal $H, \text{KN/m}^2$	
1	I	60	0,6,12,18,24	Away From Wall Face
2	I	60	0,5,10	Towards Wall Face
3	I	80	0,3,6,9,12,15	Away From Wall Face
4	II	60	0,7,14,21	Away From Wall Face
5	II	60	0,5,10,15,20	Towards Wall Face
6	II	60	0,5,10,15,20	Towards Wall Face
7	II	80	0,14,28	Away From Wall Face
8	II	80	0,5,10,12.8,15.6	Towards Wall Face
9	II	100	0,10,20,30	Away From Wall Face
10	II	100	0,5,10,15,20	Away From Wall Face
11	II	100	0,6.5,13,19.5,26	Towards Wall Face
12	III	60	0,6,12,18	Away From Wall Face
13	III	60	0,5,10,15	Towards Wall Face
14	III	100	0,5,10,15,20,23.23.25	Away From Wall Face
15	III	100	0,5,10,15,17.6	Towards Wall Face
16	IV	60	0,6,12,18,21	Away From Wall Face
17	IV	60	0,5,10,15,17.4	Towards Wall Face
18	IV	100	0,5,10,15,20	Away From Wall Face
19	IV	100	0,5,10,15,20	Towards Wall Face

Table 4.1 Values of Strip Stress for Test no. 1, $q = 60 \text{ KN/m}^2$;
Load Location I.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2°	13.26	14.18	3.53	1.20	2.78	0.73
3	20.33	22.99	12.16	10.16	6.32	2.69
4	19.95	0.00	15.35	10.79	6.53	2.78
5	16.50	18.61	13.99	9.29	0.00	1.83
6	14.17	16.33	14.08	9.61	3.97	1.27
8	13.17	14.32	12.12	4.86	-0.23	
10	10.08	9.63	3.85	-0.54		
	$H = 6 \text{ KN/m}^2$					
2	10.54	13.19	1.63	-0.37	0.71	-0.06
3	17.76	21.54	9.53	7.64	3.95	1.41
4	19.05	0.00	15.29	10.13	5.57	2.01
5	15.36	18.93	14.80	9.84	0.00	1.46
6	14.00	16.33	15.05	10.43	4.21	1.10
8	12.80	14.25	12.41	5.25	-0.13	
10	9.87	9.80	4.10	-0.50		
	$H = 12 \text{ KN/m}^2$					
2	7.39	13.66	0.67	-0.91	-7.73	-0.62
3	13.84	18.79	6.21	4.33	0.90	-0.28
4	15.91	0.00	14.81	8.54	3.53	0.56
5	12.82	18.05	15.65	10.17	0.00	0.73
6	13.22	15.99	16.09	11.56	4.30	0.63
8	11.99	13.77	12.83	5.93	-0.11	
10	9.30	9.71	4.40	-0.50		
	$H = 18 \text{ KN/m}^2$					
2	6.39	15.07	0.69	-0.84	-2.09	-1.01
3	11.44	16.44	4.20	2.46	-0.75	-1.29
4	12.28	0.00	14.36	7.20	1.94	-0.46
5	9.99	15.88	15.90	10.15	0.00	0.12
6	12.20	14.79	16.49	12.43	4.26	2.74
8	10.98	13.09	13.11	6.56	-0.06	
10	8.71	9.57	4.79	-0.50		
	$H = 24 \text{ KN/m}^2$					
2	7.15	17.31	2.85	-0.16	-3.23	-1.14
3	10.68	14.91	2.28	0.84	-1.73	-2.11
4	9.95	0.00	13.91	6.17	00.84	-1.13
5	7.80	13.75	15.79	10.02	0.00	-0.32
6	11.28	13.39	16.38	12.97	4.21	0.04
8	10.03	12.31	13.19	7.01	-0.02	
10	8.10	9.33	5.05	-0.54		

note : strain gauges 1 to 39 read left to right from bottom of each table upwards.

: zero stress values indicate faulty strain gauge.

Table 4.2 Values of Strip Stress for Test no. 2, $q = 60 \text{ KN/m}^2$;
Load Location I; Load Towards the Wall Face.

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Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	11.10	13.89	3.00	1.11	3.39	0.73
3	16.78	22.42	10.31	9.24	6.18	2.37
4	18.98	0.00	14.16	9.75	6.20	2.38
5	16.68	19.34	14.36	9.37	0.00	2.09
6	14.20	16.03	14.27	9.44	3.73	1.33
8	11.64	13.42	11.21	3.61	-0.10	
10	6.41	8.53	3.68	-0.28		
Strip Level	$H = 5 \text{ KN/m}^2$					
	$H = 5 \text{ KN/m}^2$					
2	14.17	15.61	3.04	0.91	3.85	0.95
3	21.18	25.93	11.23	10.35	7.22	2.85
4	22.53	0.00	14.05	9.95	6.93	2.86
5	19.58	21.51	14.36	8.88	0.00	2.60
6	16.85	18.16	15.33	9.19	3.88	1.80
8	13.95	15.63	12.58	3.68	1.71	
10	7.90	9.74	3.98	-0.22		
Strip Level	$H = 10 \text{ KN/m}^2$					
	$H = 10 \text{ KN/m}^2$					
2	18.42	17.64	3.16	0.45	3.47	0.90
3	26.42	29.82	12.97	11.99	8.59	3.32
4	26.51	0.00	14.66	11.10	8.34	3.36
5	24.06	23.66	13.66	8.88	0.00	3.19
6	20.20	20.38	15.37	8.39	4.51	2.45
8	17.07	18.14	13.78	3.94	0.68	
10	10.19	11.26	4.13	-0.19		

Table 4.3 Values of Strip Stress for Test no. 3, $q = 80 \text{ KN/m}^2$;
Load Location I; Load Away From the Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	19.72	20.89	4.57	3.23	3.39	0.88
3	25.83	30.94	18.89	12.16	9.01	4.81
4	23.55	30.04	20.99	12.86	7.52	2.78
5	21.85	0.00	23.22	13.82	6.76	2.90
6	16.54	19.95	16.61	10.73	5.43	1.98
8	15.54	17.74	13.70	5.38	0.48	
10	10.38	10.90	3.87	-0.85		
	$H = 3 \text{ KN/m}^2$					
2	18.51	20.34	3.12	1.92	2.05	0.26
3	25.36	31.27	18.28	11.52	8.48	4.39
4	23.24	30.55	21.48	12.86	7.43	2.57
5	21.54	0.00	23.98	14.32	6.93	2.76
6	16.43	20.01	17.02	11.19	5.72	1.90
8	15.54	17.76	13.87	5.58	0.48	
10	10.30	10.94	3.91	-0.85		
	$H = 6 \text{ KN/m}^2$					
2	16.63	19.75	1.86	7.62	8.36	-0.19
3	23.29	30.59	16.76	9.97	6.92	3.30
4	22.03	30.53	21.50	12.26	6.77	1.97
5	20.49	0.00	24.60	14.52	6.83	2.33
6	15.92	19.84	17.39	11.60	5.89	1.67
8	15.19	17.53	13.83	5.77	0.44	
10	10.14	10.92	4.00	-0.78		
	$H = 9 \text{ KN/m}^2$					
2	14.26	19.33	1.06	0.62	-0.02	-0.47
3	20.85	29.65	15.30	8.43	5.46	2.37
4	20.56	30.08	21.52	11.68	6.17	1.54
5	19.14	0.00	25.05	14.63	6.64	1.89
6	15.22	19.45	17.65	11.99	6.05	1.43
8	14.80	17.20	13.93	5.97	4.00	
10	9.89	10.83	4.08	-0.74		
	$H = 12 \text{ KN/m}^2$					
2	12.79	19.04	0.43	-0.53	-0.75	-0.75
3	18.30	28.41	13.80	6.86	3.98	1.41
4	19.06	29.30	21.50	11.04	5.50	1.11
5	17.73	0.00	25.52	14.87	6.49	1.76
6	14.35	18.91	17.92	12.45	6.16	1.23
8	14.36	16.84	14.02	6.18	3.61	
10	9.65	10.73	4.17	-0.72		

Table 4.3 (cont.) Values of Strip Stress for Test no. 3; $q = 80 \text{ KN/m}^2$;
Load Location I; Load Away From the Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 15 \text{ KN/m}^2$					
2	11.17	18.94	-0.16	-1.07	-1.65	-1.05
3	15.76	26.86	12.25	5.27	2.44	4.01
4	17.79	28.34	21.69	10.46	4.86	0.68
5	16.76	0.00	26.26	15.24	6.38	1.61
6	13.74	18.51	18.32	13.10	6.43	1.14
8	14.05	16.63	14.44	6.66	0.42	
10	9.43	10.72	4.41	-0.63		

Table 4.4 Values of Strip Stress for Test no. 4, $q = 60 \text{ KN/m}^2$;
Load Location II; Load Away From the Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	-1.17	3.37	5.28	1.81	1.65	0.24
3	6.24	9.95	14.43	8.19	4.78	2.27
4	8.82	11.66	15.23	13.27	6.75	2.47
5	6.25	8.74	12.10	12.35	6.04	1.32
6	8.11	8.70	10.72	11.11	5.51	5.49
8	5.49	6.36	7.39	3.78	-0.27	
10	5.20	5.89	1.83	-0.42		
	$H = 7 \text{ KN/m}^2$					
2	-1.58	2.61	5.28	0.54	-0.06	-0.04
3	4.11	6.67	12.63	5.63	2.06	0.38
4	6.06	8.53	13.49	12.54	5.14	1.51
5	4.78	6.99	11.02	12.33	5.60	0.97
6	6.40	7.63	9.96	11.22	5.68	0.45
8	4.67	5.63	7.11	4.39	-0.15	
10	4.60	5.65	2.28	-0.26		
	$H = 14 \text{ KN/m}^2$					
2	-1.25	2.26	7.51	7.42	-2.53	0.11
3	2.34	3.99	9.63	3.63	-0.71	-1.99
4	2.81	4.63	9.67	11.98	3.20	-0.13
5	2.77	4.38	8.49	12.07	5.38	0.41
6	5.26	5.80	8.19	10.89	6.20	0.43
8	3.43	4.44	6.29	5.02	0.21	
10	3.68	4.97	2.60	-0.02		
	$H = 21 \text{ KN/m}^2$					
2	4.54	4.66	14.34	2.53	-15.40	0.69
3	1.25	2.51	7.61	3.00	-1.37	-2.81
4	1.09	2.46	6.92	11.10	1.73	-1.32
5	1.31	2.59	6.49	11.27	5.23	0.14
6	3.66	4.34	6.63	10.17	6.39	0.43
8	2.64	3.63	5.49	5.32	0.46	
10	2.99	4.34	2.75	0.20		

Table 4.5 Values of Strip Stress for Test no. 5, $q = 60 \text{ KN/m}^2$;
Load Location II; Load Towards the Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	-1.47	4.06	5.94	2.64	3.26	0.32
3	9.50	13.16	15.99	9.01	5.39	2.50
4	10.58	14.84	18.50	14.53	6.20	3.49
5	10.65	14.31	16.85	15.41	0.00	2.64
6	9.26	11.50	13.70	14.38	8.95	2.33
8	8.59	9.23	11.06	8.22	1.50	
10	5.53	7.51	3.63	-0.07		
	$H = 5 \text{ KN/m}^2$					
2	-1.49	4.26	6.55	2.95	3.68	0.24
3	10.66	14.71	17.18	9.22	5.72	2.75
4	11.98	16.67	20.02	14.71	6.10	3.47
5	11.90	15.94	18.28	15.95	0.00	2.64
6	10.32	12.64	14.84	15.12	8.79	2.23
8	9.66	10.23	11.97	8.46	1.46	
10	6.23	8.21	3.85	-0.13		
	$H = 10 \text{ KN/m}^2$					
2	-1.62	4.04	6.98	3.15	4.16	-0.06
3	12.25	16.87	18.27	9.53	6.24	3.10
4	14.25	19.54	21.91	14.41	6.08	3.53
5	14.15	18.71	20.44	16.19	0.00	2.80
6	12.13	14.66	16.80	16.11	8.37	2.31
8	11.35	11.92	13.51	8.87	1.77	
10	7.54	9.35	4.26	-0.07		
	$H = 15 \text{ KN/m}^2$					
2	-1.64	3.35	6.99	3.09	4.53	-0.41
3	14.86	19.87	19.09	10.35	7.05	3.42
4	17.44	23.35	23.44	13.71	6.39	3.66
5	17.13	22.25	22.47	15.41	0.00	3.21
6	14.89	17.43	19.11	16.39	7.33	2.53
8	13.74	14.17	15.39	9.08	2.43	
10	9.70	11.13	4.58	-0.05		
	$H = 20 \text{ KN/m}^2$					
2	-1.66	2.40	7.45	3.07	4.64	-0.79
3	18.28	23.11	20.30	11.61	8.03	3.46
4	21.52	27.80	24.68	13.75	7.16	3.85
5	20.40	25.99	23.62	14.17	0.00	3.61
6	16.95	19.65	20.44	15.42	6.28	2.84
8	16.80	16.82	16.95	9.07	3.04	
10	12.90	13.39	4.88	3.15		

Table 4.6 Values of Strip Stress for Test no. 6, $q = 60 \text{ KN/m}^2$;
Load Location II; Load Towards the Wall.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	7.34	5.20	6.57	2.58	1.90	0.65
3	8.72	11.28	15.68	6.45	3.02	7.64
4	10.47	12.61	17.57	12.22	4.35	1.17
5	8.92	11.44	14.05	12.41	0.00	0.26
6	6.31	7.85	10.39	10.43	4.69	-0.59
8	4.81	5.32	5.89	2.85	-0.26	
10	3.29	3.35	0.39	-0.24		
	$H = 5 \text{ KN/m}^2$					
2	7.56	5.47	7.04	3.01	2.45	0.09
3	10.04	12.99	16.95	6.80	3.79	1.35
4	12.21	14.58	19.15	12.52	4.71	1.65
5	10.25	13.04	15.34	12.92	0.00	0.61
6	7.23	8.85	11.42	11.00	4.61	0.08
8	5.67	6.13	6.54	2.83	-0.30	
10	3.89	3.82	3.55	-0.26		
	$H = 10 \text{ KN/m}^2$					
2	0.86	5.55	7.34	3.32	2.99	0.11
3	12.00	15.32	18.33	7.56	4.91	2.07
4	14.81	17.47	21.10	12.60	5.43	2.30
5	12.34	15.38	17.14	13.35	0.00	1.24
6	8.67	10.32	12.84	11.67	4.53	0.47
8	6.83	7.20	7.30	2.75	-0.21	
10	4.71	4.41	0.26	-0.27		
	$H = 15 \text{ KN/m}^2$					
2	1.12	5.51	7.53	3.52	3.55	0.65
3	14.59	18.30	19.50	8.76	6.28	2.91
4	18.10	20.93	22.91	12.48	6.57	3.14
5	15.05	18.35	19.03	13.43	0.00	2.07
6	10.47	12.16	14.44	12.09	4.57	1.02
8	8.44	8.70	8.20	2.60	0.00	
10	5.91	5.18	0.11	-0.31		
	$H = 20 \text{ KN/m}^2$					
2	1.10	4.43	7.39	3.50	3.85	-0.09
3	18.01	21.85	20.32	10.46	7.71	3.60
4	22.23	25.30	24.27	12.84	8.14	4.10
5	18.49	21.91	20.63	13.03	0.00	2.99
6	12.38	14.08	15.88	11.96	4.80	1.73
8	10.53	10.50	9.06	2.44	0.50	
10	7.57	6.17	-0.24	-0.31		

Table 4.7 Values of Strip Stress for Test no. 7, $q = 80 \text{ KN/m}^2$;
Load Location II; Load Away From the Wall.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	-3.31	4.10	8.75	2.33	2.19	0.32
3	7.35	13.85	20.58	13.15	6.63	3.04
4	9.74	18.16	23.38	19.58	9.24	4.03
5	11.98	17.85	21.19	19.87	9.77	3.70
6	12.94	15.24	17.92	18.72	11.04	2.96
8	9.04	13.15	13.98	10.47	1.94	
10	10.53	9.69	4.77	-0.07		
Strip Level	$H = 14 \text{ KN/m}^2$					
	$H = 14 \text{ KN/m}^2$					
2	-4.36	3.64	9.10	0.52	-0.94	0.15
3	3.71	7.94	18.12	8.53	1.50	-1.00
4	3.48	10.64	19.25	18.31	5.60	1.13
5	6.57	12.20	18.06	19.80	8.55	2.46
6	10.19	11.97	15.58	18.89	11.12	2.47
8	5.99	10.79	13.13	11.55	2.58	
10	8.92	9.22	5.80	0.43		
Strip Level	$H = 28 \text{ KN/m}^2$					
	$H = 28 \text{ KN/m}^2$					
2	-3.26	10.74	17.93	8.78	-3.22	1.16
3	3.59	7.00	15.27	4.22	-2.97	-5.05
4	-0.56	5.88	12.47	18.01	2.16	-2.15
5	1.29	6.39	11.62	18.84	7.97	1.18
6	6.29	7.82	10.83	17.47	11.81	2.04
8	2.83	7.95	10.94	12.65	3.23	
10	7.16	7.99	6.56	1.04		

Table 4.8 Values of Strip Stress for Test no. 8, $q = 80 \text{ KN/m}^2$;
Load Location II; Load Towards the wall.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	3.48	10.14	11.04	3.79	2.53	0.88
3	9.47	16.07	22.41	12.08	6.73	2.85
4	12.89	18.94	21.97	16.91	7.80	2.55
5	12.85	0.00	21.91	18.33	10.31	3.03
6	12.29	14.27	16.44	16.64	10.08	2.43
8	12.01	13.88	13.28	9.21	1.41	
10	7.46	8.28	4.19	-2.04		
Strip Level	$H = 5 \text{ KN/m}^2$					
	$H = 5 \text{ KN/m}^2$					
2	3.89	11.34	11.77	3.87	3.03	1.05
3	11.78	19.27	24.60	11.87	6.96	3.07
4	15.07	22.04	24.54	17.16	7.43	2.53
5	14.80	0.00	24.55	19.55	9.90	3.16
6	13.82	15.91	18.11	17.77	9.87	2.55
8	13.79	15.71	14.69	9.49	1.50	
10	8.47	9.29	4.45	-0.35		
Strip Level	$H = 10 \text{ KN/m}^2$					
	$H = 10 \text{ KN/m}^2$					
2	4.21	12.32	11.85	4.08	3.57	1.23
3	14.86	23.51	26.28	11.39	7.66	3.51
4	18.19	26.27	27.28	16.24	7.24	2.70
5	17.52	0.00	27.89	20.40	9.73	3.56
6	15.92	18.21	20.22	18.71	9.25	3.00
8	16.33	18.32	16.44	9.52	2.01	
10	10.04	10.68	4.77	-0.31		
Strip Level	$H = 12.8 \text{ KN/m}^2$					
	$H = 12.8 \text{ KN/m}^2$					
2	4.45	12.79	11.61	4.14	3.78	1.36
3	17.15	26.77	26.94	11.31	8.35	3.90
4	20.67	29.76	29.03	15.54	7.39	2.87
5	19.30	0.00	30.06	20.47	9.82	4.01
6	17.50	19.90	21.60	18.88	8.79	3.33
8	18.33	20.26	17.58	9.36	2.51	
10	11.35	11.71	4.84	-0.24		
Strip Level	$H = 15.6 \text{ KN/m}^2$					
	$H = 15.6 \text{ KN/m}^2$					
2	4.60	12.90	11.22	4.16	4.03	1.48
3	19.37	29.88	27.15	11.56	9.11	4.28
4	23.00	33.00	30.22	15.00	7.67	3.08
5	20.85	0.00	31.71	20.19	10.09	4.41
6	18.93	21.41	22.67	18.63	8.45	3.65
8	20.20	22.14	18.49	9.13	3.02	
10	12.62	12.66	4.86	-0.06		

Table 4.9 Values of Strip Stress for Test no. 9, $q = 100 \text{ KN/m}^2$;
Load Location II; Load Away From the Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	1.60	5.01	11.16	2.68	2.61	0.58
3	9.40	17.84	30.41	14.34	8.56	2.41
4	16.53	0.00	31.38	25.67	12.95	4.81
5	13.23	17.89	25.21	25.26	0.00	4.20
6	13.82	18.91	20.29	22.15	13.27	3.70
8	14.88	17.76	19.13	11.66	1.82	
10	11.82	12.77	7.20	0.31		
	$H = 10 \text{ KN/m}^2$					
2	1.88	5.15	12.79	1.17	0.75	-0.37
3	6.51	12.99	29.34	10.47	4.49	-0.33
4	12.73	0.00	28.90	24.36	10.06	3.11
5	9.91	13.99	23.41	25.36	0.00	3.29
6	12.31	16.57	19.32	22.77	13.36	3.31
8	13.72	16.68	19.42	12.80	1.90	
10	10.83	12.60	7.97	0.48		
	$H = 20 \text{ KN/m}^2$					
2	3.52	8.11	17.77	0.02	-0.39	-1.01
3	5.77	10.70	28.97	6.92	0.49	-2.67
4	8.88	0.00	23.60	23.68	6.79	0.75
5	5.57	8.66	18.89	25.21	0.00	1.99
6	9.29	12.51	16.04	22.67	13.67	2.74
8	12.09	14.88	19.04	14.27	2.00	
10	9.57	12.01	8.77	0.76		
	$H = 30 \text{ KN/m}^2$					
2	10.35	17.78	32.72	-7.62	1.09	-1.05
3	8.75	13.98	32.08	4.28	-8.68	-3.84
4	6.56	0.00	18.56	23.40	3.94	-1.23
5	3.24	5.53	15.03	25.19	0.00	0.99
6	6.92	9.44	12.88	22.09	14.05	2.47
8	11.08	13.61	18.49	15.40	2.19	
10	8.64	11.37	9.29	0.98		

Table 4.10 Values of Strip Stress for Test no. 10, $q = 100 \text{ KN/m}^2$; Load Location II; Load Away From Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	3.63	7.80	15.36	4.73	3.70	1.14
3	9.18	15.54	26.92	15.13	7.22	3.04
4	13.44	21.20	27.43	21.53	9.03	2.57
5	12.85	0.00	27.59	23.39	10.49	3.84
6	14.54	18.10	20.12	20.32	11.54	3.55
8	11.95	13.63	14.82	9.84	1.52	
10	8.88	11.11	5.33	-0.37		
	$H = 5 \text{ KN/m}^2$					
2	3.07	7.02	14.91	2.70	1.80	0.04
3	7.99	13.94	27.13	14.06	5.64	2.04
4	12.15	19.87	27.47	21.64	8.07	2.03
5	11.92	0.00	27.86	24.11	10.22	3.67
6	14.44	17.73	20.44	21.11	11.85	3.65
8	11.80	13.46	15.31	10.53	1.79	
10	8.83	11.50	5.83	-0.19		
	$H = 10 \text{ KN/m}^2$					
2	2.66	6.07	15.06	10.51	0.00	-0.73
3	6.36	11.07	26.69	12.38	3.18	0.38
4	10.01	16.71	26.27	21.44	6.52	0.98
5	10.31	0.00	26.92	24.46	9.54	3.05
6	13.78	16.74	20.10	21.60	12.06	3.55
8	11.25	12.86	15.49	11.23	1.94	
10	8.47	11.33	6.23	-0.06		
	$H = 15 \text{ KN/m}^2$					
2	2.53	5.55	15.67	-0.70	-2.26	-1.68
3	5.12	8.65	26.36	11.15	0.78	-1.41
4	8.14	13.52	24.58	21.61	5.07	-0.11
5	8.59	0.00	25.29	24.79	8.97	2.33
6	12.81	15.32	19.29	21.92	12.31	3.37
8	10.59	12.08	15.43	11.96	2.07	
10	8.08	11.11	6.64	0.19		
	$H = 20 \text{ KN/m}^2$					
2	2.25	4.84	17.03	-2.66	-5.25	-2.41
3	4.07	6.72	24.98	9.46	-2.44	-5.04
4	5.75	9.83	21.02	22.13	3.56	-1.43
5	6.85	0.00	22.03	25.11	8.57	1.44
6	11.32	13.26	17.54	22.05	12.86	3.14
8	9.58	10.87	14.99	12.87	2.28	
10	7.50	10.66	7.11	0.50		

Table 4.11: Values of Strip Stress for Test no. 11, $q = 100 \text{ KN/m}^2$;
Load Location II; Load Towards the Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	4.49	8.14	12.89	2.74	2.01	0.41
3	12.82	18.95	28.65	10.75	6.84	2.39
4	15.14	0.00	27.76	21.35	10.38	4.47
5	14.17	18.07	23.39	22.38	0.00	-1.24
6	15.79	18.53	20.62	21.28	10.75	2.63
8	17.34	18.47	18.89	10.66	6.84	
10	12.01	12.64	5.72	-0.43		
	$H = 6.5 \text{ KN/m}^2$					
2	4.90	9.03	12.95	26.16	2.03	0.39
3	15.45	22.28	31.03	10.92	7.37	2.56
4	17.33	0.00	30.38	21.69	10.20	4.43
5	16.54	20.12	25.40	23.05	0.00	-1.34
6	17.42	19.99	22.36	22.39	10.37	2.53
8	18.95	20.20	20.41	10.88	0.49	
10	13.22	13.84	6.00	-0.59		
	$H = 13 \text{ KN/m}^2$					
2	5.51	9.85	12.55	2.55	2.01	0.37
3	18.59	26.46	33.04	10.79	8.05	2.73
4	20.70	0.00	33.17	21.15	10.04	4.47
5	19.50	23.22	27.93	23.13	0.00	-1.34
6	19.78	22.35	24.53	23.22	9.70	2.72
8	21.28	22.60	22.12	10.79	7.41	
10	14.98	15.20	6.12	-0.83		
	$H = 19.5 \text{ KN/m}^2$					
2	6.09	10.37	12.10	2.45	2.01	0.34
3	22.09	30.98	34.44	10.92	8.87	2.81
4	24.40	0.00	35.52	20.30	10.24	4.62
5	22.55	26.61	30.30	22.46	0.00	-1.16
6	22.50	25.00	26.77	23.37	9.02	3.02
8	24.27	25.59	24.07	10.60	1.44	
10	16.57	16.62	5.91	-1.06		
	$H = 26 \text{ KN/m}^2$					
2	5.85	9.65	11.65	22.87	2.01	0.23
3	27.23	37.13	35.75	11.37	10.04	2.81
4	30.16	0.00	38.04	19.60	11.00	4.83
5	28.02	31.94	33.33	21.19	0.00	-0.45
6	26.50	28.76	29.45	22.52	8.33	3.39
8	29.06	30.03	26.24	10.40	2.49	
10	19.99	18.66	5.48	-0.99		

Table 4.12 Values of Strip Stress for Test no. 12, $q = 60 \text{ KN/m}^2$;
Load Location III; Load Away From Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	0.32	2.59	7.78	4.88	2.47	0.86
3	2.22	4.73	9.72	11.20	4.96	1.76
4	2.33	7.96	11.33	14.08	7.82	2.38
5	2.90	0.00	10.35	13.19	9.12	2.46
6	3.81	5.39	7.77	10.68	8.89	2.12
8	2.48	4.42	6.25	6.16	1.25	
10	5.96	6.23	3.98	0.56		
	$H = 6 \text{ KN/m}^2$					
2	0.86	2.38	7.55	4.18	0.98	0.17
3	1.76	3.73	8.28	11.01	3.51	0.57
4	1.40	6.70	10.11	13.74	7.41	1.88
5	2.14	0.00	9.24	12.93	9.14	2.25
6	3.29	4.47	7.09	10.57	9.16	2.18
8	2.23	4.09	6.27	6.49	1.43	
10	5.85	6.21	4.19	0.65		
	$H = 12 \text{ KN/m}^2$					
2	0.02	2.15	6.92	3.67	-0.69	-1.20
3	1.29	2.97	5.78	10.47	1.54	-0.97
4	0.53	5.27	8.00	12.97	6.90	1.20
5	1.40	0.00	7.48	12.25	9.18	1.97
6	2.56	3.39	5.83	9.95	9.39	2.14
8	1.96	3.65	5.97	6.77	1.58	
10	5.63	6.08	4.36	0.80		
	$H = 18 \text{ KN/m}^2$					
2	0.00	1.93	5.98	3.79	-2.17	-1.96
3	0.87	2.77	3.61	9.67	-0.78	-2.83
4	0.17	4.11	5.82	11.51	6.60	0.45
5	0.69	0.00	5.56	10.99	9.52	1.76
6	1.73	2.26	4.33	8.84	9.72	2.14
8	1.26	3.13	5.51	7.03	1.81	
10	5.25	5.78	4.43	0.93		

Table 4.13 Values of Strip Stress for Test no. 13, $q = 60 \text{ KN/m}^2$;
Load Location III; Load Towards Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	1.03	3.60	8.53	6.98	3.30	0.97
3	1.70	5.44	11.23	13.33	6.79	2.45
4	3.03	7.57	11.77	15.07	10.54	2.46
5	13.80	0.00	13.17	15.30	12.15	2.82
6	6.22	7.76	9.96	11.96	10.12	2.55
8	3.67	5.97	7.60	6.72	1.16	
10	3.31	5.07	2.67	0.06		
	$H = 5 \text{ KN/m}^2$					
2	1.21	4.24	10.65	6.61	3.53	1.10
3	2.59	6.88	13.88	14.62	6.73	2.81
4	4.66	9.98	14.60	16.99	10.18	2.40
5	1.64	0.00	15.76	17.27	11.94	2.97
6	7.60	9.39	11.91	13.71	10.37	2.69
8	4.95	7.45	9.06	7.38	1.14	
10	4.08	6.02	2.96	0.06		
	$H = 10 \text{ KN/m}^2$					
2	1.18	4.53	12.34	6.35	3.89	1.14
3	3.87	8.54	16.45	14.77	7.04	3.17
4	6.53	12.66	17.47	18.10	9.86	2.33
5	2.90	0.00	18.34	18.81	11.34	3.33
6	9.11	11.15	14.02	15.42	10.18	3.20
8	6.32	9.04	10.56	7.85	1.46	
10	4.73	6.88	3.18	0.11		
	$H = 15 \text{ KN/m}^2$					
2	1.32	5.16	15.14	5.83	4.37	1.29
3	4.63	10.97	19.83	14.42	8.09	3.71
4	9.43	16.68	21.33	18.38	10.12	2.33
5	4.83	0.00	22.06	20.06	10.75	3.86
6	11.32	13.65	16.95	17.31	9.56	3.88
8	8.52	11.56	12.77	8.26	2.24	
10	5.89	8.19	3.40	0.09		

Table 4.14 Values of Strip Stress for Test no. 14, $q = 100 \text{ KN/m}^2$;
Load Location III; Load Away From Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	0.69	2.65	12.08	3.21	2.40	0.65
3	4.33	7.66	15.17	18.42	6.88	2.43
4	6.83	13.87	17.32	22.49	11.03	2.38
5	7.40	0.00	18.60	21.15	14.76	2.88
6	10.58	10.77	16.36	18.95	15.11	2.96
8	9.91	13.00	14.57	13.47	2.38	
10	3.16	7.24	5.37	0.56		
	$H = 5 \text{ KN/m}^2$					
2	0.52	2.48	12.28	2.55	1.34	0.04
3	3.85	6.81	14.86	18.57	5.56	1.45
4	6.08	13.03	16.61	22.58	10.42	1.82
5	6.74	0.00	17.19	21.21	14.90	2.67
6	10.21	10.14	16.04	19.06	15.48	2.86
8	9.64	12.67	14.63	13.86	2.47	
10	2.73	7.16	5.57	0.67		
	$H = 10 \text{ KN/m}^2$					
2	0.52	2.53	12.36	2.60	7.32	0.37
3	3.35	5.92	13.38	18.64	4.21	0.36
4	5.32	11.91	15.35	22.38	9.75	1.09
5	6.00	0.00	16.65	20.97	15.01	2.37
6	9.53	9.22	15.24	18.88	15.78	2.72
8	9.23	12.19	14.44	14.12	2.55	
10	2.45	7.01	5.70	0.76		
	$H = 15 \text{ KN/m}^2$					
2	0.58	2.67	12.22	2.64	0.42	-0.71
3	3.02	5.73	11.56	18.77	2.85	-0.69
4	4.56	10.18	13.67	22.00	9.07	0.41
5	5.24	0.00	14.94	20.47	15.20	2.10
6	8.74	8.19	14.10	18.46	16.19	2.63
8	8.75	11.58	14.10	14.40	2.62	
10	2.17	6.78	5.78	0.85		
	$H = 20 \text{ KN/m}^2$					
2	0.56	2.69	11.95	2.68	-0.50	-1.00
3	2.83	4.95	10.00	18.81	1.58	-1.74
4	4.05	10.02	12.20	21.46	8.50	-0.17
5	4.62	0.00	13.44	19.86	15.48	1.91
6	7.99	7.30	13.00	17.95	16.55	2.59
8	8.28	10.94	13.66	14.66	2.74	
10	1.95	6.53	5.89	0.96		

Table 4.14 (cont.) Values of Strip Stress for Test no. 14, $q = 100 \text{ KN/m}^2$;
Load Location VII; Load Away From Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 23.25 \text{ KN/m}^2$					
2	7.13	2.96	11.63	3.30	-0.86	-1.14
3	2.79	4.82	7.97	18.96	-0.37	-3.40
4	3.24	9.12	10.17	20.46	7.73	-0.98
5	4.00	0.00	11.49	18.92	16.01	1.65
6	7.07	6.20	11.50	17.13	17.20	2.53
8	7.61	10.06	12.94	14.94	2.85	
10	1.61	6.17	5.97	1.11		

Table 4.15 Values of Strip Stress for Test no. 15, $q = 100\text{KN/m}^2$;
Load Location III; Load Towards Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	1.12	4.12	17.97	6.47	3.53	0.60
3	7.23	10.65	21.95	20.76	5.73	1.66
4	11.21	15.22	20.53	24.05	9.27	1.84
5	11.14	0.00	23.00	25.22	1.40	2.50
6	3.83	8.71	12.62	16.94	14.15	2.80
8	0.00	10.37	12.29	11.22	1.94	
10	6.50	7.48	3.80	0.15		
	$H = 5 \text{ KN/m}^2$					
2	1.17	4.43	19.32	6.82	3.93	0.77
3	7.96	11.59	23.88	21.43	5.75	1.97
4	12.38	16.90	22.70	25.81	8.88	2.01
5	12.35	0.00	25.22	26.88	14.03	2.67
6	4.40	9.60	13.82	18.16	14.40	2.69
8	0.00	11.14	13.13	11.59	1.81	
10	7.11	8.08	3.95	0.09		
	$H = 10 \text{ KN/m}^2$					
2	1.27	4.84	20.71	6.57	4.37	0.95
3	9.03	13.03	26.32	21.13	5.79	2.31
4	13.97	19.05	25.38	27.18	8.24	2.25
5	14.18	0.00	28.38	29.04	13.65	3.05
6	5.28	10.96	15.58	19.83	14.36	2.74
8	0.00	12.29	14.31	12.03	1.75	
10	7.95	8.83	4.15	0.11		
	$H = 15 \text{ KN/m}^2$					
2	1.27	5.38	22.50	5.89	4.62	1.18
3	10.27	14.94	29.59	19.62	6.36	2.73
4	16.37	22.19	29.01	27.69	7.88	2.57
5	17.09	0.00	32.95	31.44	13.12	3.63
6	6.72	13.11	18.26	22.11	13.90	3.00
8	0.00	14.28	16.15	12.31	1.82	
10	7.13	9.18	4.04	0.07		
	$H = 17.6 \text{ KN/m}^2$					
2	1.45	6.06	24.46	5.38	4.56	1.33
3	11.47	16.73	31.97	18.51	7.06	3.10
4	18.34	24.60	31.63	27.24	7.90	2.80
5	19.30	0.00	36.16	32.61	12.91	4.01
6	7.78	14.64	20.03	23.31	13.40	3.18
8	0.00	15.40	17.14	12.35	2.01	
10	8.47	9.95	4.15	0.13		

Table 4.16 Values of Strip Stress for Test no. 16, $q = 60 \text{ KN/m}^2$;
Load Location IV; Load Away From Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	0.17	0.66	1.00	1.98	4.62	0.88
3	1.41	1.95	3.48	5.16	11.00	2.29
4	1.27	1.98	3.61	6.10	12.55	2.57
5	0.67	0.00	3.51	5.71	10.77	2.99
6	1.20	1.57	2.47	4.42	8.20	2.72
8	0.72	1.94	3.08	8.82	2.34	
10	0.82	2.02	2.00	1.18		
	$H = 6 \text{ KN/m}^2$					
2	0.32	0.91	1.33	2.04	4.81	0.04
3	1.41	1.86	3.00	4.02	11.31	1.34
4	1.02	1.48	2.74	4.73	12.46	2.20
5	4.76	0.00	2.64	4.62	10.52	2.97
6	0.88	1.12	1.88	3.70	7.97	2.86
8	0.52	1.56	2.70	8.65	2.51	
10	0.67	1.78	2.06	1.39		
	$H = 12 \text{ KN/m}^2$					
2	0.50	0.93	1.47	2.12	6.31	0.62
3	1.54	1.88	2.71	3.03	11.41	0.03
4	0.87	1.03	1.90	3.12	11.74	1.82
5	0.31	0.00	1.85	3.29	9.80	3.18
6	0.53	0.60	1.18	2.67	7.37	3.16
8	0.25	1.17	2.11	8.20	2.72	
10	0.41	1.34	1.91	1.61		
	$H = 18 \text{ KN/m}^2$					
2	1.12	1.41	2.12	2.50	12.98	0.37
3	1.18	1.66	2.38	2.24	11.13	1.80
4	1.10	1.01	1.63	2.38	10.20	1.37
5	0.14	0.00	1.43	2.46	8.39	3.60
6	0.28	0.22	0.74	1.94	6.45	3.63
8	0.97	0.86	1.71	7.68		
10	0.22	0.99	1.74	1.93		
	$H = 21 \text{ KN/m}^2$					
2	2.07	2.63	3.33	3.96	17.01	0.24
3	3.13	2.26	2.94	2.51	13.36	3.76
4	2.06	1.53	2.09	2.68	10.61	0.86
5	1.45	0.00	1.38	2.38	8.18	3.67
6	0.24	0.52	0.06	1.45	6.01	3.70
8	0.02	0.69	1.52	7.55	3.12	
10	0.13	0.86	1.68	1.94		

Table 4.17 Values of Strip Stress for Test no. 17, $q = 60 \text{ KN/m}^2$;
Load Location IV; Load Towards Wall Face.

Strip Level	Strip Stress Values, $\text{N/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	0.06	0.37	0.82	1.55	3.80	0.77
3	0.57	1.17	2.46	3.83	10.30	2.14
4	1.25	2.45	3.76	5.82	11.82	2.72
5	0.98	0.00	4.45	6.93	11.28	2.59
6	2.04	2.64	3.50	5.43	8.58	2.67
8	0.45	2.23	3.67	5.43	2.15	
10	2.49	3.78	3.39	1.22		
	$H = 5 \text{ KN/m}^2$					
2	0.02	0.29	0.80	1.48	3.97	0.88
3	0.83	1.56	2.98	3.36	10.88	2.27
4	1.72	3.12	4.54	6.76	12.76	2.70
5	1.29	0.00	5.29	8.00	12.19	2.59
6	2.45	3.12	4.10	6.22	9.35	2.53
8	0.70	2.67	4.18	5.93	2.01	
10	2.90	4.30	3.70	1.18		
	$H = 10 \text{ KN/m}^2$					
2	0.09	0.12	0.61	1.22	3.89	0.92
3	1.13	1.98	3.48	4.90	11.23	2.35
4	2.44	4.17	5.63	8.03	13.95	2.59
5	1.81	0.00	6.60	9.55	13.55	2.76
6	3.17	3.95	5.09	7.46	10.54	2.47
8	0.83	3.11	4.90	6.70	1.86	
10	3.44	4.94	4.13	1.04		
	$H = 15 \text{ KN/m}^2$					
2	0.19	0.04	0.41	0.85	3.45	0.92
3	1.54	2.55	4.15	5.55	10.57	2.43
4	3.22	5.42	6.84	9.50	14.46	2.23
5	2.52	0.00	8.37	11.62	14.97	3.03
6	4.25	5.18	6.55	9.29	12.12	2.61
8	1.38	4.13	6.19	7.94	1.75	
10	4.17	5.80	4.73	0.83		
	$H = 17.4 \text{ KN/m}^2$					
2	0.28	0.08	0.41	0.80	3.28	0.92
3	1.81	2.93	4.61	6.02	9.93	2.52
4	3.56	5.98	7.36	10.12	14.14	2.08
5	2.90	0.00	9.29	12.64	15.33	3.20
6	4.80	5.80	7.37	10.26	12.79	2.74
8	1.67	4.65	6.96	8.86	1.81	
10	4.64	6.34	5.07	0.73		

Table 4.18 Values of Strip Stress for Test no. 18, $q = 100 \text{ KN/m}^2$;
Load Location IV, Load-Away From Wall Face.

Strip Level	Strip Stress Values, $\text{KN/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	0.82	1.90	2.63	4.64	6.98	0.90
3	0.00	2.88	4.97	8.49	21.20	2.87
4	2.14	4.02	5.95	10.34	22.17	3.27
5	2.26	0.00	7.09	11.25	20.95	4.94
6	0.40	1.75	3.52	7.05	15.36	4.82
8	1.84	5.30	3.80	10.84	5.21	
10	3.59	4.69	5.25	2.52		
	$H = 5 \text{ KN/m}^2$					
2	0.58	1.68	2.26	4.02	6.79	0.13
3	0.00	2.71	4.28	7.09	21.74	1.64
4	1.97	3.48	4.92	8.99	22.45	2.68
5	1.60	0.00	5.76	10.03	21.12	4.75
6	0.11	1.22	2.72	6.17	15.32	4.82
8	1.51	4.69	3.27	10.88	5.59	
10	3.29	4.41	5.31	2.83		
	$H = 10 \text{ KN/m}^2$					
2	0.47	1.47	1.98	3.50	7.00	-0.45
3	0.00	2.77	4.05	5.70	22.60	4.01
4	1.95	3.23	4.11	7.34	22.66	2.16
5	1.21	0.00	4.59	8.46	21.16	4.69
6	0.04	0.90	2.11	5.17	15.21	5.00
8	1.11	4.18	2.55	10.79	5.97	
10	3.09	4.06	5.22	3.09		
	$H = 15 \text{ KN/m}^2$					
2	0.28	1.20	1.71	3.11	7.02	-0.88
3	2.51	3.06	4.21	5.09	22.91	-0.80
4	2.08	3.20	3.76	6.19	22.28	1.69
5	1.00	0.00	3.93	7.28	20.78	4.71
6	-0.02	0.71	1.69	4.36	14.80	5.21
8	0.86	3.76	2.03	10.55	6.40	
10	2.82	3.68	5.09	3.38		
	$H = 20 \text{ KN/m}^2$					
2	0.15	1.08	1.65	2.95	7.67	-1.16
3	3.17	3.59	4.63	4.83	23.01	-2.50
4	2.14	3.31	3.59	5.35	21.21	1.09
5	0.86	0.00	3.46	6.32	19.95	4.88
6	-0.11	0.54	1.31	3.63	14.04	5.59
8	0.58	3.30	2.36	10.17	7.01	
10	2.56	3.27	4.88	3.74		

Table 4.19 Values of Strip Stress for Test no. 19, $q = 100 \text{ KN/m}^2$;
Load Location IV; Load Towards Wall Face.

Strip Level	Strip Stress Values, $\text{KN/m}^2 \times 10^7$					
	$H = 0 \text{ KN/m}^2$					
2	0.93	1.93	2.47	3.36	8.30	0.90
3	0.00	2.48	4.55	6.75	16.58	3.13
4	3.82	5.40	7.03	10.51	19.26	3.62
5	2.74	0.00	7.61	10.51	17.28	4.11
6	3.61	4.92	6.59	10.04	15.15	4.55
8	2.35	4.01	6.42	8.97	4.31	
10	3.91	4.30	4.02	2.24		
	$H = 5 \text{ KN/m}^2$					
2	0.89	1.95	2.47	3.36	8.63	0.95
3	0.00	2.80	4.91	7.22	17.36	3.09
4	4.30	6.04	7.72	11.36	20.28	3.42
5	2.98	0.00	8.32	11.34	18.19	3.90
6	4.01	5.33	7.20	10.85	16.03	4.35
8	2.48	4.21	6.84	9.49	4.16	
10	4.17	4.66	4.34	2.18		
	$H = 10 \text{ KN/m}^2$					
2	0.80	1.84	2.39	3.09	8.57	0.95
3	0.00	3.26	5.38	7.78	18.00	3.06
4	4.98	6.86	8.50	12.37	21.45	3.30
5	3.43	0.00	9.19	12.34	19.31	3.77
6	4.51	5.91	7.98	11.83	17.09	4.10
8	2.79	4.63	7.43	10.16	3.90	
10	4.54	5.09	4.66	2.02		
	$H = 15 \text{ KN/m}^2$					
2	0.69	1.72	2.29	2.66	8.28	0.99
3	0.00	3.70	5.82	8.28	18.14	3.13
4	5.62	7.68	9.31	13.44	22.30	3.21
5	3.90	0.00	10.15	13.52	20.48	3.82
6	5.34	6.70	9.01	13.10	18.34	3.94
8	3.07	5.09	8.11	10.96	3.55	
10	4.96	5.57	5.05	1.85		
	$H = 20 \text{ KN/m}^2$					
2	0.56	1.59	2.16	2.06	7.92	0.99
3	0.00	4.08	6.20	8.66	17.78	3.29
4	6.32	8.49	10.09	14.49	22.68	3.19
5	4.50	0.00	11.29	14.78	22.07	3.94
6	6.20	7.50	10.13	14.48	19.60	3.90
8	3.05	5.40	8.72	11.72	3.25	
10	5.37	6.12	5.46	1.61		

Table 4.20 Wall Deflection Readings, (mm); Test no.1.

Level	Horizontal Load Component Values, KN/m^2				
	0	6	12	18	24
1	1.40	1.07	0.18	-0.99	-2.84
2	1.27	1.14	0.69	0.13	-0.43
3	0.89	0.86	0.64	0.36	-1.00
4	0.69	0.66	0.58	0.30	0.30
5	0.43	0.43	0.41	0.36	0.28
6	0.28	0.28	0.28	0.25	0.23
7	0.18	0.20	0.20	0.18	0.18
8	0.18	0.18	0.20	0.20	0.20
9	0.15	0.15	0.15	0.15	0.15
10	0.13	0.13	0.13	0.13	0.13

Table 4.21 Wall Deflection Readings, (mm); Test no.2.

Level	Horizontal Load Component Values, KN/m^2		
	0	5	10
1	2.01	2.69	4.37
2	1.73	2.26	3.56
3	1.22	1.57	2.44
4	0.76	0.99	1.45
5	0.51	0.64	0.91
6	0.33	0.41	0.56
7	0.23	0.28	0.41
8	0.20	0.25	0.33
9	0.18	0.23	0.28
10	0.10	0.13	0.15

Table 4.22 Wall Deflection Readings, (mm); Test no.3.

Level	Horizontal Load Component Values, KN/m^2					
	0	3	6	9	12	15
1	2.24	2.21	2.03	1.80	1.50	1.12
2	1.75	1.73	1.63	1.50	1.35	1.14
3	1.36	1.32	1.30	1.22	1.14	1.04
4	0.91	0.91	0.91	0.89	0.86	0.81
5	0.70	0.70	0.70	0.69	0.69	0.69
6	0.48	0.48	0.51	0.51	0.51	0.51
7	0.41	0.41	0.41	0.41	0.41	0.41
8	0.43	0.43	0.43	0.43	0.43	0.43
9	0.25	0.25	0.25	0.25	0.25	0.25
10	0.15	0.15	0.15	0.15	0.15	0.13

Table 4.23 Wall Deflection Readings, (mm); Test no.4.

Level	Horizontal Load Component Values, KN/m^2			
	0	7	14	21
1	0.28	-0.56	-1.40	-3.38
2	0.66	0.51	0.20	-0.66
3	0.76	0.71	0.58	0.48
4	0.51	0.48	0.43	0.41
5	0.48	0.48	0.43	0.41
6	0.33	0.33	0.33	0.33
7	0.33	0.33	0.33	0.33
8	0.30	0.30	0.30	0.30
9	0.18	0.18	0.18	0.18
10	0.20	0.20	0.20	0.20

Table 4.24 Wall Deflection Readings, (mm); Test no.5.

Level	Horizontal Load Component Values, KN/m^2				
	0	7	14	21	28
1	0.36	0.51	0.99	1.98	3.68
2	0.64	0.79	1.14	1.93	3.28
3	0.69	0.79	1.12	1.70	2.72
4	0.56	0.64	0.81	1.22	1.91
5	0.51	0.58	0.71	0.99	1.45
6	0.38	0.41	0.51	0.69	0.99
7	0.36	0.38	0.46	0.58	0.81
8	0.36	0.38	0.43	0.53	0.71
9	0.23	0.25	0.30	0.38	0.48
10	0.46	0.48	0.56	0.66	0.76

Table 4.25 Wall Deflection Readings, (mm); Test no.6.

Level	Horizontal Load Component Values, KN/m^2				
	0	5	10	15	20
1	0.03	0.05	0.23	0.58	1.22
2	0.20	0.28	0.30	0.74	1.27
3	0.18	0.05	0.36	0.56	0.91
4	0.15	0.20	0.28	0.41	0.64
5	0.10	0.13	0.18	0.25	0.38
6	0.08	0.10	0.13	0.18	0.25
7	0.05	0.05	0.08	0.10	0.15
8	0.03	0.05	0.05	0.08	0.10
9	0.03	0.03	0.03	0.05	0.08
10	0.03	0.03	0.03	0.03	0.05

Table 4.26 Wall Deflection Readings, (mm); Test no.8.

Level	Horizontal Load Component Values, KN/m^2				
	0	5	10	12.8	15.6
1	0.61	0.84	1.32	1.83	2.46
2	0.79	0.97	1.98	1.75	2.18
3	0.71	0.64	1.17	1.50	1.85
4	0.64	0.74	0.94	1.17	1.40
5	0.48	0.56	0.69	0.84	1.02
6	0.43	0.48	0.58	0.69	0.76
7	0.36	0.41	0.48	0.56	0.64
8	0.30	0.36	0.41	0.48	0.53
9	0.20	0.25	0.28	0.30	0.33
10	0.20	0.23	0.25	0.30	0.33

Table 4.27 Wall Deflection Readings, (mm); Test no.9.

Level	Horizontal Load Component Values, KN/m^2			
	0	10	20	30
1	1.19	0.69	0.36	-0.84
2	1.40	1.07	0.48	-0.76
3	1.34	1.19	0.86	0.36
4	1.14	1.04	0.79	0.66
5	0.97	0.97	0.86	0.79
6	0.71	0.69	0.66	0.66
7	0.71	0.71	0.71	0.71
8	0.51	0.53	0.53	0.51
9	0.38	0.38	0.38	0.41
10	0.38	0.38	0.38	0.41

Table 4.28 Wall Deflection Readings, (mm); Test no.10.

Level	Horizontal Load Component Values, KN/m ²				
	0	5	10	15	20
1	0.64	0.51	0.25	-0.10	-0.71
2	0.84	0.76	0.61	0.41	0.03
3	0.84	0.81	0.71	0.56	0.38
4	0.76	0.79	0.74	0.66	0.53
5	0.64	0.66	0.64	0.58	0.53
6	0.48	0.53	0.53	0.51	0.51
7	0.51	0.53	0.53	0.53	0.53
8	0.46	0.48	0.48	0.51	0.51
9	0.25	0.28	0.28	0.28	0.28
10	0.15	0.18	0.18	0.18	0.18

Table 4.29 Wall Deflection Readings, (mm); Test no.11.

Level	Horizontal Load Component Values, KN/m ²				
	0	6.5	13	19.5	26
1	0.79	1.02	1.45	2.16	3.58
2	0.84	1.02	1.40	2.01	3.20
3	0.84	0.99	1.27	1.73	2.62
4	0.64	0.71	0.91	1.22	1.85
5	0.53	0.61	0.74	0.97	1.40
6	0.38	0.43	0.51	0.66	1.09
7	0.30	0.36	0.41	0.51	0.71
8	0.28	0.30	0.36	0.43	0.58
9	0.18	0.20	0.23	0.28	0.33
10	0.08	0.08	0.10	0.10	0.13

Table 4.30 Wall Deflection Readings, (mm); Test no.12.

Level	Horizontal Load Component Values, KN/m^2			
	0	6	12	18
1	0.38	0.28	0.03	-0.43
2	0.48	0.66	0.25	0.03
3	0.51	0.48	0.28	0.30
4	0.46	0.48	0.43	0.36
5	0.43	0.46	0.43	0.66
6	0.46	0.48	0.48	0.48
7	0.38	0.41	0.41	0.41
8	0.28	0.30	0.30	0.30
9	0.18	0.18	0.18	0.18
10	0.13	0.13	0.13	0.13

Table 4.31 Wall Deflection Readings, (mm); Test no.13.

Level	Horizontal Load Component Values, KN/m^2			
	0	5	10	15
1	0.64	0.94	1.42	2.41
2	0.58	0.79	1.12	1.73
3	0.64	0.81	1.07	1.50
4	0.53	0.66	0.84	1.14
5	0.43	0.53	0.66	0.89
6	0.33	0.38	0.48	0.61
7	0.30	0.38	0.46	0.56
8	0.30	0.36	0.41	0.51
9	0.20	0.25	0.28	0.33
10	0.18	0.20	0.23	0.25

Table 4.32 Wall Deflection Readings, (mm); Test no.14.

Level	Horizontal Load Component Values, KN/m^2				
	0	5	10	15	20
1	0.56	0.46	0.28	0.03	-0.28
2	0.74	0.69	0.58	0.43	0.25
3	0.81	0.79	0.71	0.64	0.53
4	0.74	0.74	0.69	0.64	0.56
5	0.64	0.64	0.64	0.61	0.58
6	0.53	0.53	0.53	0.53	0.51
7	0.51	0.51	0.51	0.51	0.51
8	0.38	0.38	0.38	0.38	0.38
9	0.28	0.30	0.30	0.30	0.30
10	0.28	0.28	0.28	0.28	0.28

Table 4.33 Wall Deflection Readings, (mm); Test no.15.

Level	Horizontal Load Component Values, KN/m^2				
	0	5	10	15	17.6
1	0.51	0.69	1.04	1.83	2.64
2	0.61	0.71	0.97	1.42	1.91
3	0.69	0.76	0.94	1.24	1.52
4	0.61	0.66	0.76	0.94	1.12
5	0.79	0.56	0.66	0.79	0.91
6	0.46	0.46	0.53	0.61	0.66
7	0.38	0.38	0.46	0.51	0.56
8	0.33	0.33	0.36	0.41	0.43
9	0.23	0.23	0.28	0.30	0.33
10	0.15	0.18	0.18	0.20	0.23

Table 4.34 Wall Deflection Readings, (mm); Test no.16.

Level	Horizontal Load Component Values, KN/m ²				
	0	6	12	18	21
1	0.25	0.15	-0.18	-1.37	-3.20
2	0.25	0.20	0.05	-0.28	-0.76
3	0.25	0.20	0.13	0.00	-0.08
4	0.23	0.20	0.13	0.08	0.05
5	0.23	0.23	0.18	0.15	0.13
6	0.25	0.25	0.23	0.20	0.20
7	0.18	0.18	0.15	0.15	0.15
8	0.15	0.15	0.15	0.15	0.13
9	0.13	0.13	0.13	0.13	0.10
10	0.08	0.08	0.08	0.08	0.05

Table 4.35 Wall Deflection Readings, (mm); Test no.17.

Level	Horizontal Load Component Values, KN/m ²				
	0	5	10	15	17.4
1	0.38	0.48	0.71	1.17	1.52
2	0.30	0.36	0.31	0.81	1.04
3	0.30	0.38	0.51	0.74	0.89
4	0.28	0.30	0.38	0.53	0.64
5	0.25	0.28	0.36	0.51	0.56
6	0.23	0.23	0.28	0.36	0.41
7	0.25	0.30	0.36	0.43	0.48
8	0.20	0.28	0.33	0.41	0.43
9	0.20	0.25	0.28	0.36	0.38
10	0.15	0.15	0.18	0.20	0.23

Table 4.36 Wall Deflection Readings, (mm); Test no.18.

Level	Horizontal Load Component Values, KN/m^2				
	0	5	10	15	20
1	0.41	0.23	-0.05	-0.38	-0.94
2	0.53	0.41	0.25	0.10	-0.20
3	0.53	0.48	0.38	0.28	0.13
4	0.53	0.48	0.43	0.36	0.25
5	0.48	0.48	0.43	0.41	0.36
6	0.43	0.43	0.41	0.41	0.38
7	0.38	0.38	0.38	0.38	0.36
8	0.30	0.33	0.30	0.30	0.30
9	0.25	0.25	0.25	0.25	0.25
10	0.23	0.23	0.23	0.23	0.23

Table 4.37 Wall Deflection Readings, (mm); Test no.19.

Level	Horizontal Load Component Values, KN/m^2				
	0	5	10	16	20
1	0.43	0.53	0.69	0.94	1.24
2	0.46	0.53	0.64	0.79	1.02
3	0.43	0.51	0.58	0.69	0.84
4	0.41	0.43	0.48	0.56	0.64
5	0.38	0.43	0.46	0.53	0.61
6	0.33	0.38	0.38	0.43	0.48
7	0.30	0.36	0.36	0.41	0.56
8	0.25	0.28	0.28	0.30	0.36
9	0.20	0.23	0.23	0.25	0.28
10	0.10	0.13	0.13	0.15	0.15

Table 4.38 Average Values of Strip Elongation, (mm).

Level	Average Values of Strip Elongation																		
	Test No.																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
2	.15	.15	.23	.05	.08	.08	.08	.15	.10	.15	.13	.08	.10	.10	.15	.05	.03	.08	.08
3	.36	.30	.51	.20	.25	.20	.36	.36	.41	.38	.41	.18	.20	.28	.33	.13	.10	.23	.15
4	.30	.30	.43	.25	.30	.28	.46	.36	.51	.41	.43	.20	.23	.33	.36	.13	.13	.20	.20
5	.33	.36	.33	.23	.33	.28	.48	.33	.48	.38	.43	.18	.23	.33	.38	.13	.13	.23	.20
6	.30	.30	.36	.23	.30	.20	.46	.36	.46	.43	.43	.20	.23	.36	.28	.10	.13	.15	.23
8	.25	.23	.30	.13	.23	.10	.33	.28	.38	.30	.38	.13	.15	.30	.20	.10	.08	.15	.15
10	.20	.13	.18	.10	.13	.05	.23	.15	.23	.18	.23	.13	.08	.13	.13	.05	.08	.13	.10

Table 5.1 Calculated Values of Soil-Strip Friction Coefficient.

Level	Test No.																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
2	.84	.84	.94	.32	.38	.40	.40	.47	.42	.49	.37	.42	.56	.40	.60	.12	.15	.17	.20
3	.94	.84	.94	.65	.70	.70	.70	.76	.76	.70	.69	.42	.49	.42	.49	.35	.27	.34	.26
4	.65	.65	.70	.56	.65	.63	.65	.60	.65	.56	.62	.44	.49	.44	.47	.32	.25	.29	.25
5	.49	.52	.49	.34	.52	.42	.49	.49	.47	.42	.46	.38	.44	.36	.42	.26	.23	.25	.20
6	.40	.38	.34	.29	.38	.27	.35	.33	.34	.33	.31	.24	.32	.31	.27	.19	.16	.17	.17
8	.30	.28	.28	.16	.25	.13	.23	.23	.25	.25	.22	.15	.18	.20	.17	.12	.10	.13	.09
10	.20	.16	.14	.12	.17	.06	.16	.13	.15	.17	.11	.13	.10	.09	.09	.01	.01	.01	.01

APPENDIX III

CALIBRATION OF THE STRAIN GAUGES

Using a Universal Testing Machine, preliminary stress-strain tests on a strip instrumented with strain gauges indicated differences in the strain readings, between a dial gauge reading and the strain gauge readings, and even some differences between the strain gauge readings themselves, see Fig.3.4. These different values of strain would have led to several different values of Young's modulus for the one strip. In order to avoid any confusion in obtaining the stress values from the strain gauge readings, each strain gauge was calibrated, by performing a stress-strain test on each fully instrumented strip, prior to placement in the reinforced earth retaining wall.

The instrumented strip was suspended from a hanger through the plate used in affixing the strip to the wall face. A weight of 3 lbs., (1.36 kg.), was suspended from the free end of the strip, and all the strain gauges were zeroed. Then three load increments of 10 lbs.(4.45 kg.) each were added to the existing weight, and strain readings were taken at each increment. Knowing the cross-sectional area of the strip, ($6.45 \times 10^{-7} \text{ m}^2$), and any given load increment, the stress increment was thus determined. Thus stress-strain relationships were determined for each strain gauge, and although all different, they reflect the true stress existing in the strip.

Values of the stress-strain relationships for the gauges are presented in Table III.1. Note that strip nos. 3,4 and 5 were replaced during the experimental programme, as some of the gauges had failed.

Table III.1 Values of the Stress/Strain Ratio for the Strain Gauges.

Strip	Gauge	$\times 10^{11} \text{ N/m}^2$	Strip	Gauge	$\times 10^{11} \text{ N/m}^2$
10	1	1.87	4	22	2.15
	2	1.87		23	2.05
	3	1.87		24	1.97
	4	1.85		25	2.01
8	5	1.94	3	26	2.04
	6	1.92		27	2.09
	7	1.90		28	1.92
	8	1.86		29	2.04
	9	1.90		30	2.05
6	10	1.84	3	31	2.10
	11	1.87		32	2.08
	12	1.90		33	2.01
	13	1.88	2	34	2.16
	14	1.92		35	2.07
	15	1.96		36	2.04
5	16	2.01		37	2.06
	17	2.01		38	2.09
	18	1.93		39	2.15
	19	1.96			
	20	1.88			
	21	1.97			

Table III.1 Values of the Stress/Strain Ratio for the Strain Gauges on the Replaced Strips.

Strip	Gauge	$\times 10^{11} \text{ N/m}^2$
5	16	2.38
	17	****
	18	2.47
	19	2.18
	20	2.12
	21	2.12
4	22	2.12
	23	2.15
	24	2.11
	25	2.14
	26	2.13
	27	2.14
3	28	1.85
	29	1.82
	30	1.92
	31	1.87
	32	1.95
	33	1.91

Note: Strip 3 replaced after test no.6, strips 4 and 5 replaced after test no.11.

* Faulty gauge.

APPENDIX IV

SAMPLE CALCULATIONS

SAMPLE CALCULATIONS

From table III.1 the stress-strain ratio for gauge no. 29, strip no. 3, is $1.82 \times 10^{11} \text{ N/m}^2$, as determined by the method outlined in Appendix III.

The strain readings for this gauge for test no. 11 are as follows (strain values are micro-strain, i.e. $\times 10^{-6}$) :

H KN/m ²				
0.0	6.5	13	19.5	26
1041	1224	1454	1702	2040

multiplying the above strain readings by 1.82×10^{11} yields values of stress as follows, (stress values are $\times 10^7, \text{ N/m}^2$) :

H KN/m ²				
0.0	6.5	13	19.5	26
18.95	22.28	26.46	30.98	37.13

thus the stress increments for each horizontal load component are as follows, (stress values are $\times 10^7, \text{ N/m}^2$) :

H	0.0	6.5	13	19.5	26
Stress	0.0	3.33	7.51	12.03	18.18

Using linear regression to determine the slope of the relationship between the horizontal load component and the change in the strip stress yields a value of 6,932, (see Fig.4.60).

To adjust this value to a contour value of the ratio of the change in the soil stress to the horizontal load component, it is multiplied by a value of 6.481×10^{-5} , ($= A/(ds.dh)$).

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