MODELLING OF THE STRUCTURAL BEHAVIOURS OF CANTILEVER RETAINING WALL

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ABSTRACT

Retaining walls are engineering structures constructed to resist lateral forces imposed by soil movement and water pressure; they are used as protection against the erosive forces of water and as a method of slope stabilization along highways, railroads and construction sites. In this Study, the structural behavior of cantilever retaining wall under varying applied loading conditions and geometric properties was modeled. The limit state requirements for overturning, sliding and bearing pressure were studied under different geometric properties for wall with and without surcharge loads. The use of computer programming (Java) was employed for quick analysis of the conditions. The results showed that this wall satisfied the limit state requirement at these values of Base Width the respective surcharge loads. For wall with zero surcharge, the satisfactory value of Base Width is 0.6H and for 10kN/m^2, the Base Width equals 0.7H. The satisfactory values of Base Width for walls with surcharge loads of 20kN/m^2 and 30kN/m^2 are 0.8H and 0.9H respectively. It is evidence from the results that additional surcharge loads at back of cantilever retaining wall increase its tendency to fail and also that sliding effects are more critical than overturning.

KEYWORDS: RETAINING WALL, SURCHARGE, STABILITY, LOADINGS, SLIDING, OVERTURNING

1.0 INTRODUCTION

The problem of retaining soil was described by Al Atik and Siter (2008) as one of the oldest in geotechnical engineering. Retaining walls are permanent or temporary structures used to provide lateral support to the soil, liquid and other materials. These structures are used to retain earth fill or any other materials, which would not be able to stand vertically unsupported so that the ground surface at different elevations are maintained on either side of the retaining walls (Raju, 2000). The retained material is usually called the backfill. Valsson (2011) opined that the challenge of creating differences in terrain elevation over horizontal distance which is often done by creating slope is usually inadequate when slopes can no longer support themselves and concluded that retaining walls can solve such problems up to a point. Retaining walls are useful within the built up environment especially at bridge site, riverbank areas and even within houses in sloppy terrains (Oyenuga, 2005).

The walls provide direct support for roads; bridge decks and bridge arch supports. If unrestrained, a soil embankment will relapse to its angle of repose. Some soil, such as clays have cohesion that enables vertical and near- vertical faces to remain partially intact, but even these may slump under the softening influence of groundwater. The soil exerts an active pressure on the structure, which deflects a little and is then restrained by the friction and adhesion between the base and soil beneath, passive soil pressures in front of the structure and bearing capacity of the soil beneath the toe of the structure. Retaining walls must adequately support its backfill without detrimental lateral movement and the surface of the backfill must not settle unduly. If water is trapped behind the retaining structure, this may also reduce the adhesion and the bearing resistance. They are often designed with great heights and length to retain the movement of the soil and the rocks in ways that are both attractive and economical. If massive rock formations are present immediately behind the structure, these will restrict the volume of soil, which can be mobilized and thus reduce the pressure. As a result of the dynamic nature of developments in engineering design and product development, different types of retaining walls have evolved in quick succession.

Cantilever retaining walls constructed of reinforced Portland cement concrete was the predominant type of rigid retaining walls used from about the 1920s to the 1970s. It largely displaced the traditional gravity wall constructed of stone or unreinforced cement concrete, which may prove to be uneconomical for height above 3m, due to superior economics in the use of material and support backfill up to 7.5m high (Oyenuga, 2005). In early 1990s, segmental block gravity retaining structure, consisting of concrete units dry stacked against a soil slope, which resist overturning by virtue of their own weight and setback was introduced into Australia and rapidly become popular. A further development of this, is the boral key steel system, which utilizes steel-ladder reinforcement. Here; the steel-ladder reinforcement is placed in horizontal layers in the compacted backfill and mechanically connected to the blocks. The systems are individually engineer designed and are suitable for walls in excess of 6m in height and for critical surcharge loadings.

According to Oyenuga (2005) and Morgenstern and Sangrey (1982). Retaining walls are broadly classified into major types as Gravity, Cantilever and Revetment walls. Delattre (2001) gave the general overview of various methods used in analyzing retaining walls over the centuries from the predecessors of coulomb to Boussinesq and the limitation of a method led to the development of another which was a continuation of work done in (Delattre,2001). The safety factor against overturning must be greater or equal to 1.5 if the soil in front of the wall is ignored and greater or equal to 2.0 if the soil is allowed in front of the wall (Alam, 1992) and Ranjan and Rao (2007). Mosley *et al* (1999) said that critical conditions for stability are when a maximum horizontal force acts with a minimum vertical load and when the Overturning moment is greater than Resisting moment. To guard against a stability failure, it is usual to apply conservative factors of safety to the force and loads with a value of γ_f=1.6 or higher.

Raju (2000) also recommended the following values for the stability of cantilever retaining walls as Top width of the stem =200mm (minimum), Base width, B =0.5H to 0.6H for wall without surcharge loads and 0.7H for walls supporting surcharge loads but did not state the effects of increasing surcharge load on stability of the retaining wall, Toe Projection =B/3,Usually the thickness of base slab = Thickness of stem and Factor of safety against sliding to be greater than 1.5, which quite agrees with the specification given by Alam (1992). Ranjan and Rao (2007) also made the following recommendations that Base width, B to be 0.4H to 0.7H, Projection of toe from the base of stem to be 0.2B to 0.4B and Unit weight of granular soils may range from 16.5 to 17kN/m^2 and 17 to 19kN/m^2 for cohesive soils.

As the use of retaining walls is very crucial in a built up environment in order to retain soil, liquid and other materials, Designers have been faced over the years with the difficulty of designing retaining walls due to the fact that the design may satisfy the overturning effect but fail in sliding or in other words, the design process satisfies a process at the expense of other. According to Sundaravel and Premalatha (2013), design of cantilever retaining walls needs both geotechnical and structural considerations. They observed that this includes the complete study of earth pressure distribution and its point of application, displacement, bending moment and shear force on the wall when subjected to different kinds of loading.

The main objective of this study was to investigate the structural behaviors of cantilever retaining wall under varying applied loading conditions and geometric properties by proportioning the dimensions of the wall to allow for iterative design process to study the effect of the variations on the stability against forward sliding, overturning and bearing capacity failure. This research therefore minimized the stress associated with the iterative process of design and analyses of these structures. The deductions gave range of satisfactory dimensions with respect to the height of the wall for the preliminary dimensioning state of design.

2.0 METHODOLOGY

The major method employed in this research is numerical method and a computer program(Java) was developed to ease the analysis of cantilever retaining wall under varying application of loads based on the model advanced for the purpose. The project is also comparative in nature with the comparison of the changes in two or three parameters on the structural properties of the cantilever retaining walls. The types of loads allowed by the program to act on the structure (retaining walls) are surcharge pressure, backfill soil pressure and the self weight of the retaining walls (wall and footing). Surcharge pressure is assumed to act over the entire surface area of the backfill soil at the abutment (wall) top level which may belong to either permanent or transitory load group. The backfill soil pressure is the pressure exerted on the structure by the retained soil which maybe calculated internally by the program as a function of structure lateral displacement. Self weight of the abutment will internally be calculated by the program.

2.1 Model of the Structure

A structure model shown in Figure 1 was used to develop a program for the calculation of the overturning moment and sliding forces on the wall under varying application of loads and geometric dimensions as illustrated in the flow chart (Figure 2). The procedures followed are explained below under stability analyses and bearing pressure analyses.

2.1.1 *Stability Analysis*

The steps used are as follows:

i. The height of the retaining wall was taken to be H=3m, 5m, 7m and 9m and Width of the footing (B) was taken to be in the range of 0.5 to 1.0 of wall height, Wall thickness, $b = B/6$, toe width, c as $1/3$ of B as suggested by Raju (2000) and width of heel, d was also used as $0.5B$. A value of angle of internal friction (ϕ) was also taken to be 30degrees as stated by Smith and Smith (1990) and all these are inputted into the computer program.

ii. Determination of coefficient of active pressure, Ka from the expression:

$$K_a = {(1 - Sin\phi)}/{(1 + Sin\phi)} \quad \text{.........................} \quad (1)$$

It was assumed that the effect of passive earth pressure is zero because the wall is not retaining soil behind the stem (at toe side).

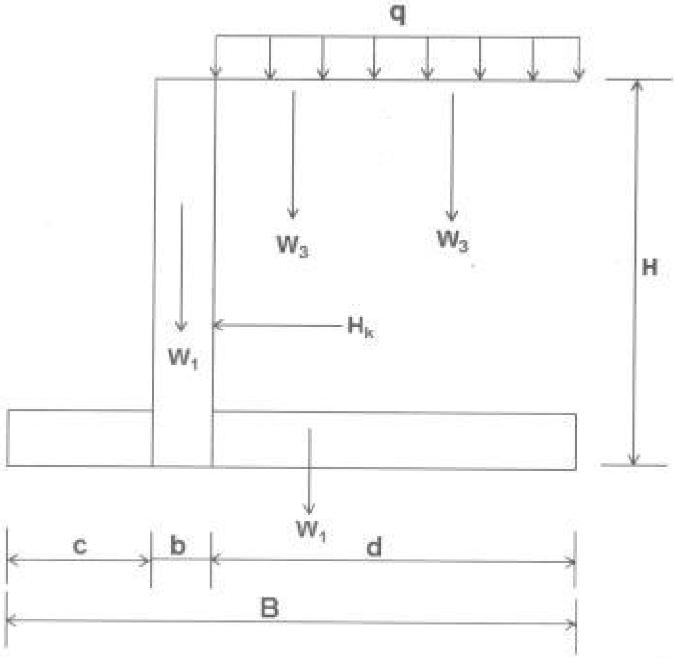

Figure 1: A Model of Cantilever Retaining Wall

iii. The next step is the calculation of lateral/horizontal earth pressure induced on the wall by the backfill soil (P_a) and surcharge load (P_s) given in the equations below

$$P_a = K_a \gamma H \text{ and } P_s = K_a q$$

Where γ is the unit weight of soil taken to be 18kN/m^3 for well-drained soil, q is the surcharge load. The Surcharge values of 0,10,20,30 and 40kN/m^2 (Fethi, 2000; Dicleli, 2001) were used as design practical values for uniform loads (roadway, building and stock goods) or dynamic load (traffic) and based on minimum design surcharge of 10kN/m^2 recommended by code of practice. After this, total horizontal force/load (H_K) was determined from the expression.

$$H_k = 0.5 K_a \gamma H^2 + P_s H \text{ .... (2)}$$

(If the wall supports the surcharge load together with the backfill soil), otherwise the surcharge effect becomes zero and for this condition, horizontal force reduces to

$$H_k = 0.5 K_a \gamma H^2 \text{ .... (3)}$$

iv. Calculation of vertical loads

The vertical loads acting on the wall are loads from surcharge (W_4), backfill soil (W_3), self weight of the stem (W_1) and self weight of the footing (W_2).The unit weight of concrete was taken as $24 kN/m^3$. These loads are calculated from the expression:

$W_1 = 24b\,(H - b)$

$W_2 = 24Bb$

$W_3 = d\gamma\,(H - b)$

$W_4 = dq$

Total vertical load $V_k = W_1 + W_2 + W_3 + W_4$ .... (4)

v. Checking for sliding

The structure will only be stable against sliding when the frictional resisting force is greater than sliding force. These forces were calculated from:

Frictional resisting force $F = \mu V_k$ .... (5)

Where μ is the coefficient of friction and its value was taken to be 0.5 in the program therefore, F becomes $0.5V_k$ and safety factor against sliding,

$$F_s = F/H_k \text{ -- (6)}$$

vi. Checking for overturning effect

For the wall to resist the overturning moment that may be developed at the toe, overturning moment must be less than resisting moment, that is

Resisting moment ≥ Overturning moment.

Overturning moment $(OM) = 0.17P_aH^2 + 0.5P_sH^2$ .... (7)

Resisting moment $R = W_1(0.5b + c) + 0.5W_2B + (W_3 + W_4)(0.5d + b + c)$ ...... (8)

The safety factor against overturning, $F_o = R/OM$

2.1.2 *Bearing Pressure Analysis*

The bearing pressures underneath retaining walls were assessed on the basis of serviceability limit state when determining the size of the base that is required. The analysis was based on foundations subjected to vertical load and horizontal (vertical load applied eccentrically) loads, coupled with an overturning moment. By considering a unit length of the cantilever wall, the resultant moment about the centroidal axis of the base was calculated as:

Moment about base center-line M

$$M = 0.17P_aH^2 + 0.5P_sH^2 + W_1(0.5B - 0.5b - c) - (W_3 + W_4)(0.5B - 0.5d) \text{ .... (9)}$$

The maximum bearing pressure was calculated from the program by the expression:

$$P_1 = \frac{V_k}{B} + \frac{6M}{B^2} \text{ and } P_2 = \frac{V_k}{B} - \frac{6M}{B^2} \text{ ------------ (10) and (11)}$$

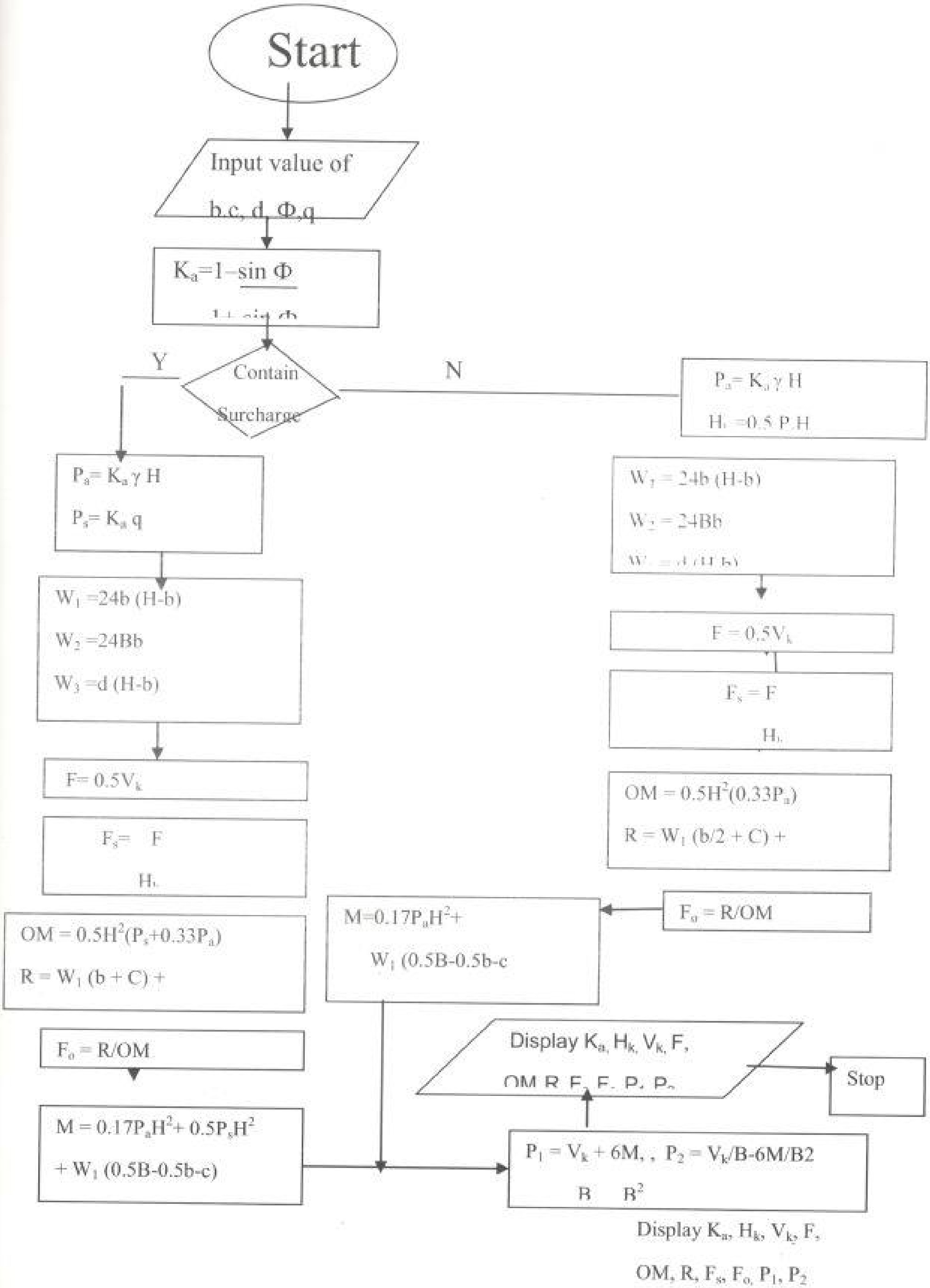
Start
Input value of
b,c, d, Φ,q
Ka=1−sin Φ
1+sin Φ
Contain
Surcharge
Y
N
Pa= Ka γ H
Ps= Ka q
W1 =24b (H-b)
W2 =24Bb
W3 =d (H-b)
F= 0.5Vk
Fs= F
Hk
OM = 0.5H2(Ps+0.33Pa)
R = W1 (b + C) +
Fo = R/OM
M = 0.17PaH2+ 0.5PsH2
+ W1 (0.5B-0.5b-c)
Pa= Ka γ H
Hk =0.5 Pa H
W1 = 24b (H-b)
W2 = 24Bb
W3 = d (H-b)
F = 0.5Vk
Fs = F
Hk
OM = 0.5H2(0.33Pa)
R = W1 (b/2 + C) +
Fo = R/OM
M=0.17PaH2+
W1 (0.5B-0.5b-c
Display Ka, Hk, Vk, F,
OM R Fs Fo P1 P2
Stop
P1 = Vk + 6M, , P2 = Vk/B-6M/B2
B B2
Display Ka, Hk, Vk, F,
OM, R, Fs, Fo, P1, P2

Figure 2: Flow Chart of the Model

3.0. RESULTS AND DISCUSSION

3.1 Behaviour of Frictional Resisting Force with Base Width and Wall Height

Figures 3 to 6 showed the structural behaviour of Base width and wall height with resisting force, for walls with and without surcharge loads. These figures expressed clearly that frictional resisting force increases constantly with a constant increase in base width but increases at an increasing rate with constant increase in wall height. The results also revealed that lateral effect remains constant for a particular wall height with varying base width but increases at an increasing rate with constant increase in height of the retaining wall. This gives an indication that higher walls are being subjected to greater effect of sliding as compared to lower ones. For surcharge effect, both resisting force and lateral thrust increase constantly with constant increase in surcharge load but the effect of lateral thrust is more prominent and therefore shows that wall supporting surcharge are more prone to sliding than walls without surcharge and this effect increases with increase in surcharge load.

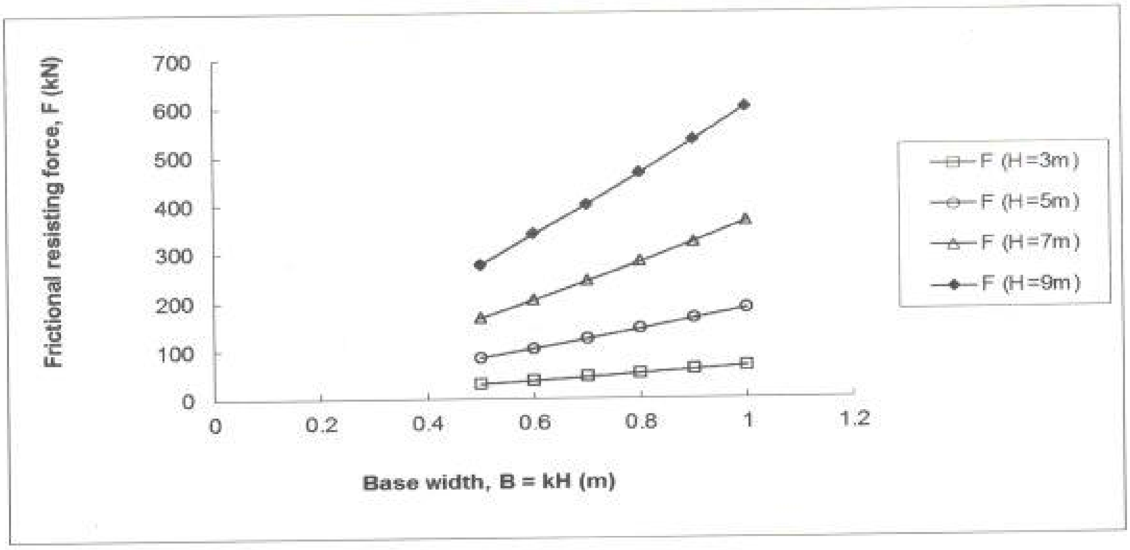

Figure 3: Behaviour of frictional resisting force against base width for zero surcharge

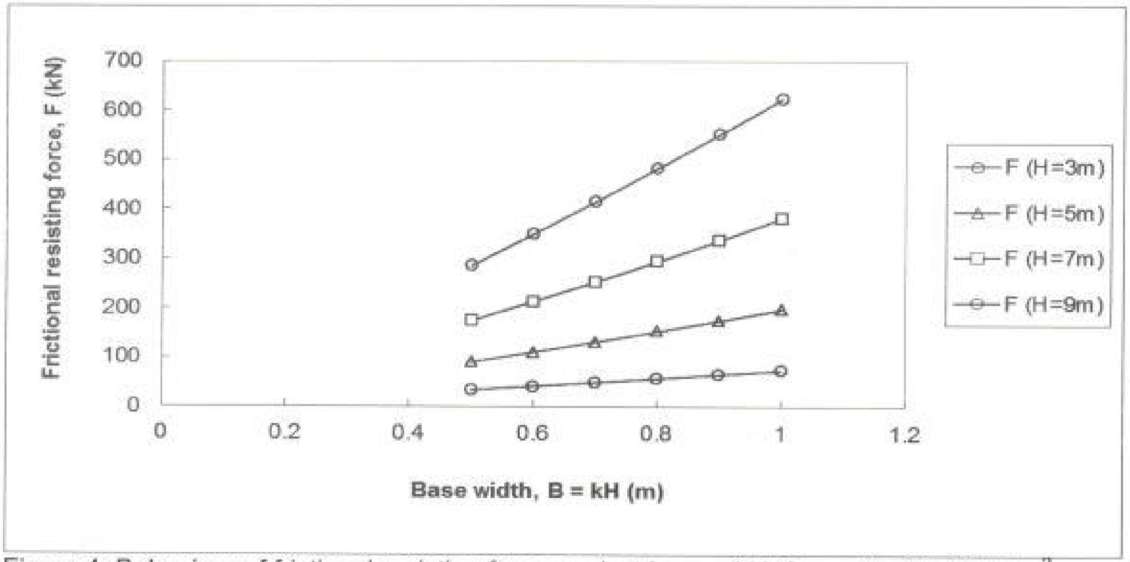

Figure 4: Behaviour of frictional resisting force against base width for wall with 10 kN/m^2 as surcharge

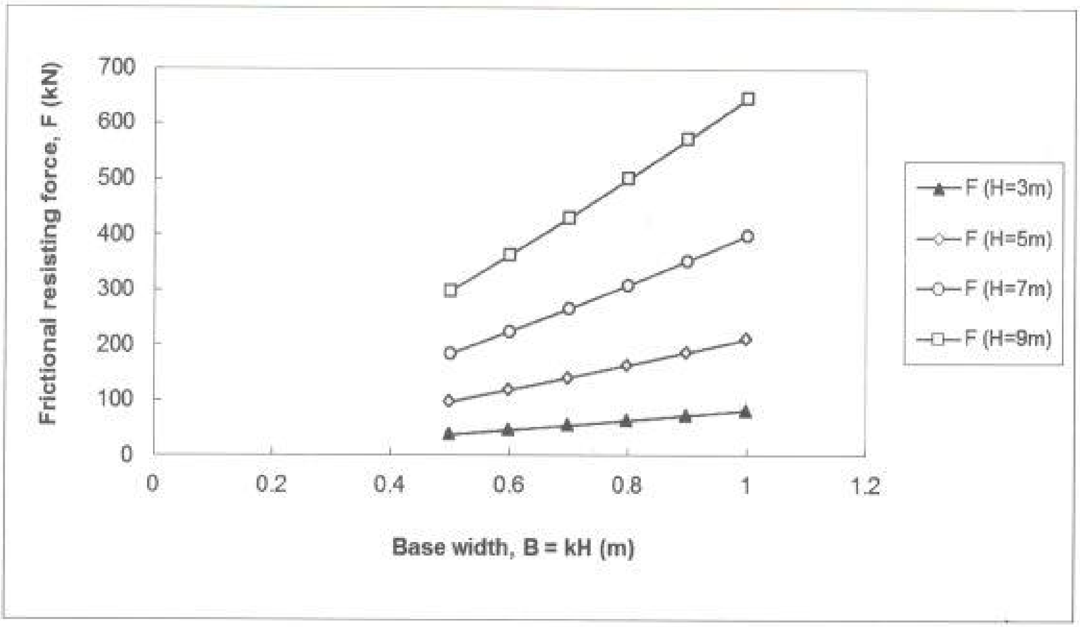

Figure 5: Behaviour of frictional resisting force against base width for wall with 20 kN/m^2 as surcharge

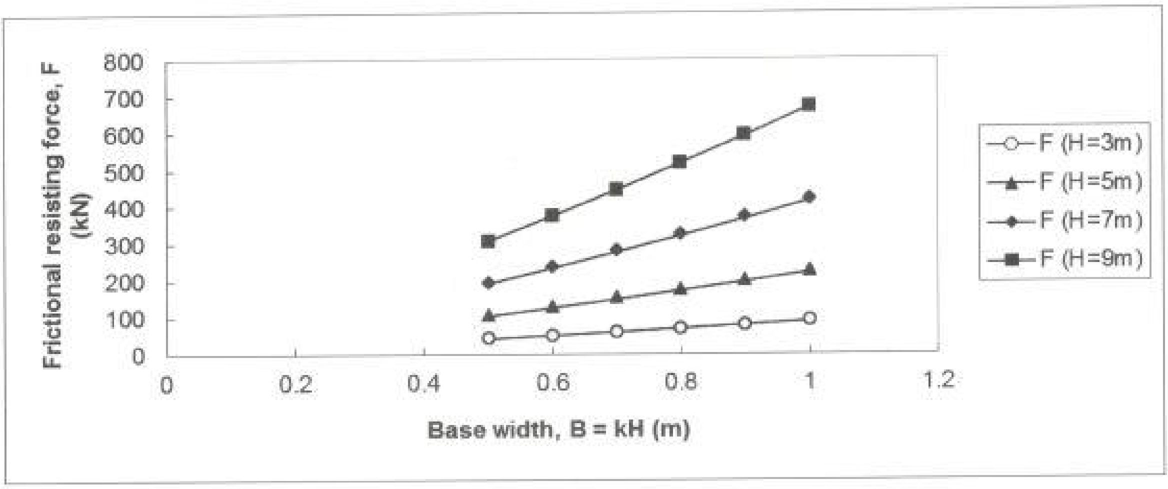

Figure 6: Behaviour of frictional resisting force against base width for wall with 30 kN/m^2 as surcharge

3.2 Behaviour of Resisting Moment with Base Width and Wall Height

From figures 7 and 8, it is clearly shown that resisting moment behaves non-linearly with base width providing a positive curvature. This implies that resisting moment increases at an increasing rate with constant increase in both wall height and Base width. The result also revealed that overturning moment increases at an increasing rate with constant increase in wall height but its value remains constant for a particular wall height with varying base width. The figures also showed that the higher the surcharge load the higher the resisting moment but greater will be the tendency for the overturning of the retaining wall to occur.

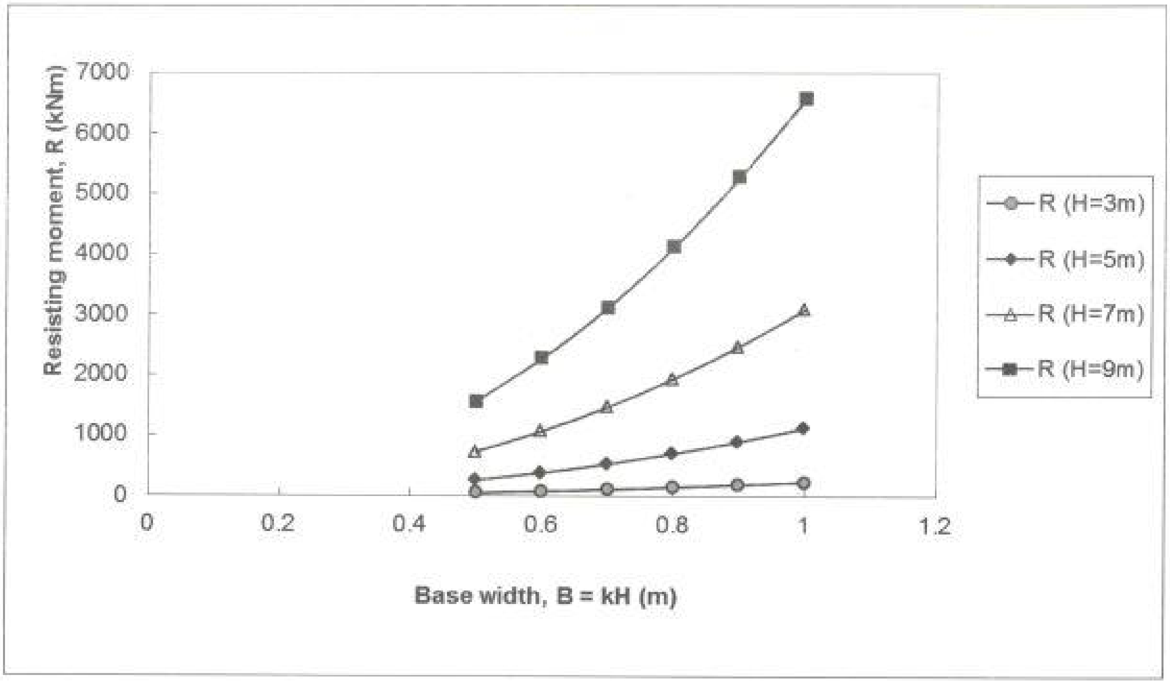

Figure 7: Behaviour of resisting moment against base width for zero surcharge

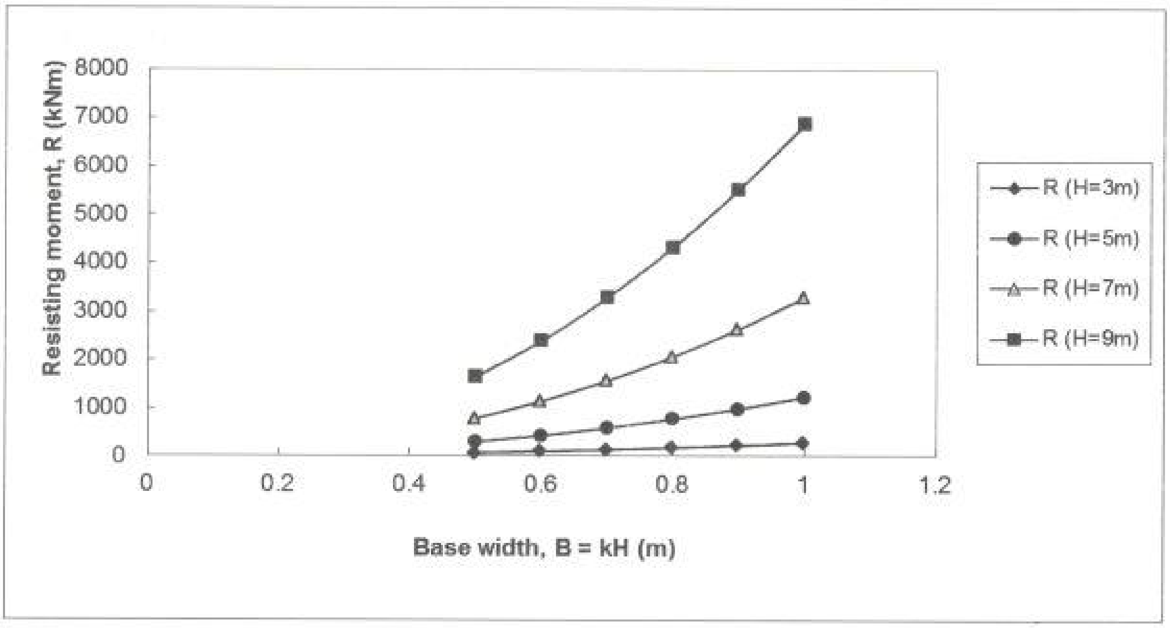

Figure 7: Behaviour of resisting moment against base width for surcharge load of 10 kN/m^2

3.3 Behaviour of Safety Factors with Base Width and Wall Height

Figures 9 to 11 showed that safety factor against overturning varies non-linearly with the base width providing a positive curvature while safety factor against sliding varies linearly with the base width. This implies that both safety factors increase with an increasing base width as overturning safety factor increases at an increasing rate while that of sliding increases constantly. Results also revealed that both factors remain constant for different wall height for walls without surcharge load. While, for walls supporting surcharge load, overturning safety factor increases at a decreasing rate with constant increase in wall height. Also it is clearly shown that these safety factors decrease constantly with an increase in surcharge values. Raju (2000) and Alam (1992) stated that factor of safety against sliding and overturning should at least be 1.5 and 2.0 respectively to cater for some unforeseen circumstances such as design errors, constructional mistakes and so on. The dimensions of Base width at these values are 0.63H and 0.49H for wall with zero surcharge, 0.70H and 0.61H for wall with surcharge of $10kN/m^2$, 0.80H and 0.61H for $20N/m^2$ as surcharge load and 0.90H and 0.66H for Wall with surcharge load of $30kN/m^2$

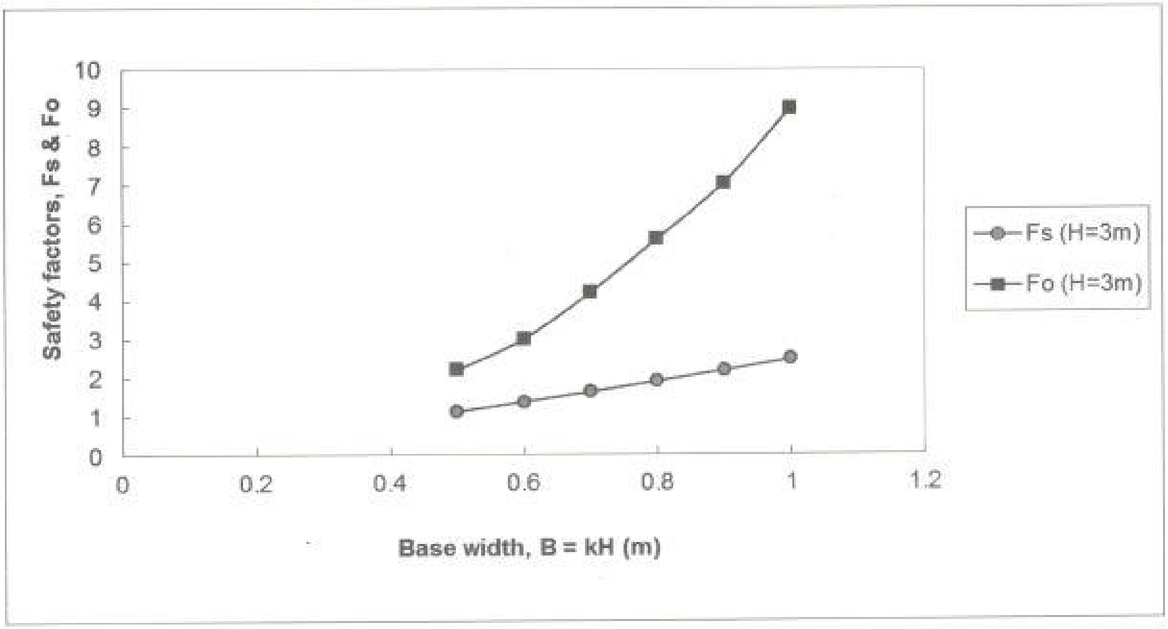

Figure 9: Relationship between factors of safety and base width for zero surcharge load

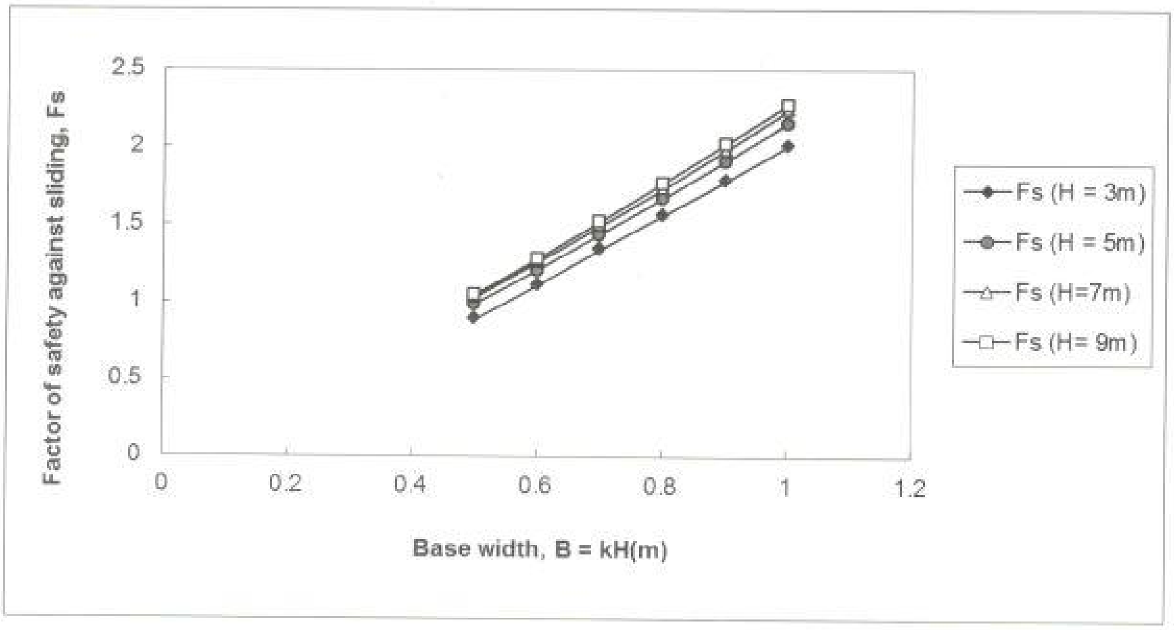

Figure 10: Relationship between factor of safety against sliding and base width for surcharge load of 10 kN/m^2

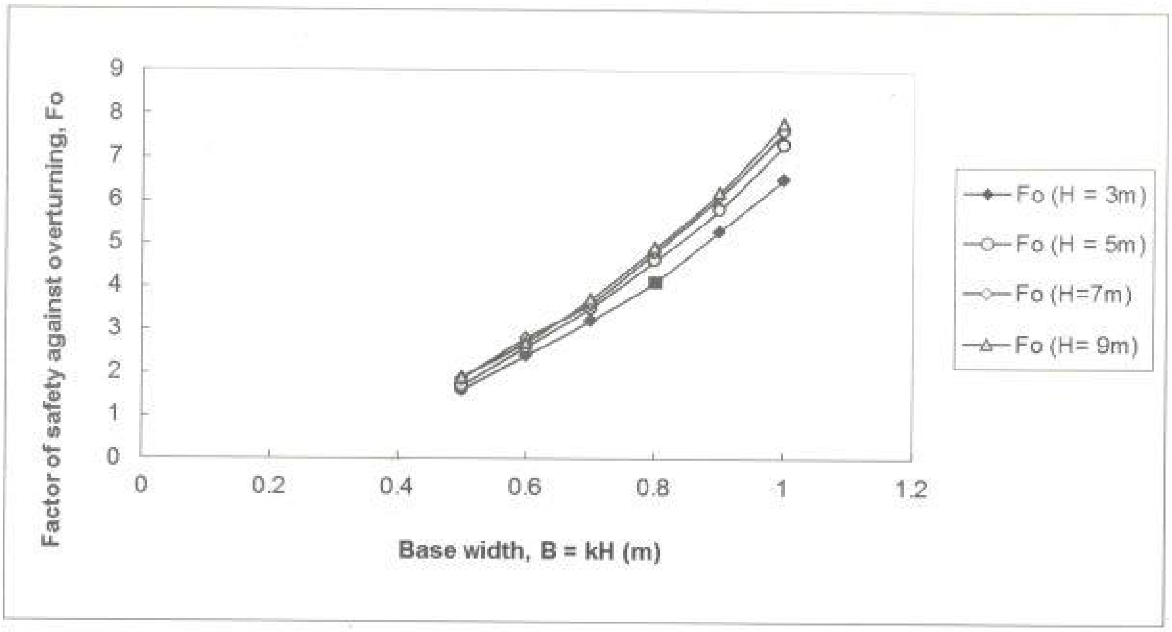

Figure 11: Relationship between factor of safety against overturning and base width for surcharge load of 10 kN/m^2

3.4 Behaviour of Base Pressures with Base Width and Wall Height.

The pressures at the base of the retaining wall vary non-uniformly with the base width as shown in figures 12-15. The pressure at the toe (P1) decreases at a decreasing rate given negative curvature as the Base width increases constantly but increases constantly as the wall height increases. The pressure developed at the heel increases at a decreasing rate from negative to positive with an increase in Base width. The negative values of the heel pressure indicated tension failure and as base width continues to increase, heel pressure reached a zero value which marked the end of tension failure in the structure and began the satisfactory performance of the wall. As base width increases further, toe and heel pressures continued decreasing and increasing respectively, a point is reached where the two pressures have the same values. This point showed that there is uniform pressure distribution at the base of the wall and also indicate that further increase of base width will cause heel pressure to be greater than toe presence (because resultant moment will be negative) thereby resulting to overturning at the toe. From figures 12 and 13, it clearly shows that surcharge values increase the risk of tension or compression of the retaining wall, that is, surcharge load increases the pressure at the base of the wall.

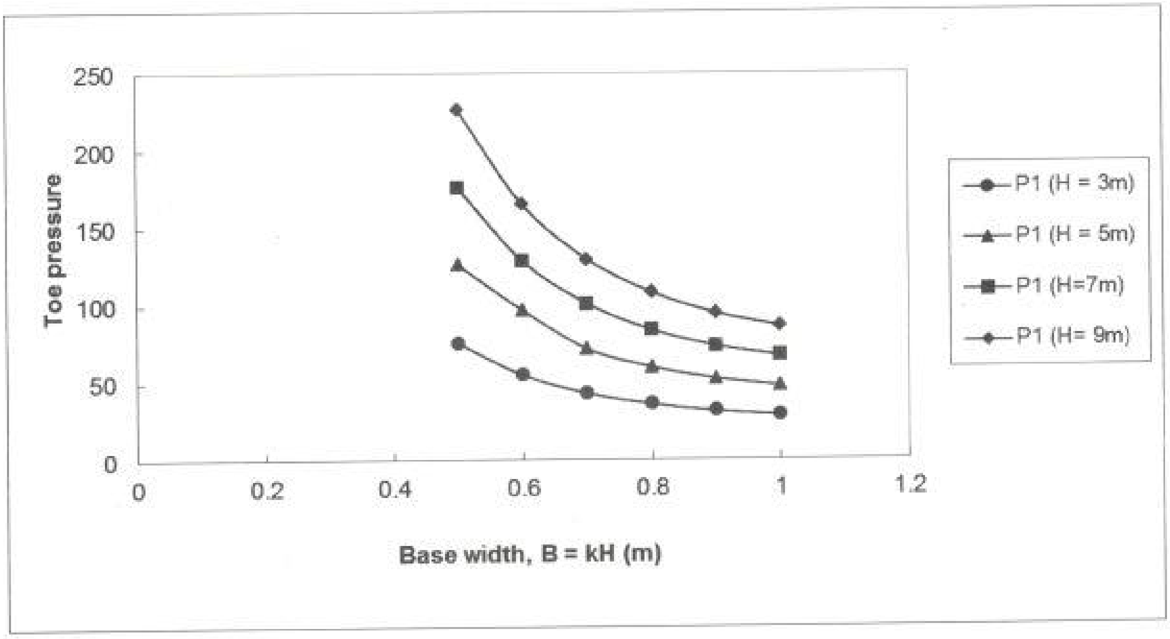

Figure 12: Behaviour of toe pressure against base width for zero surcharge

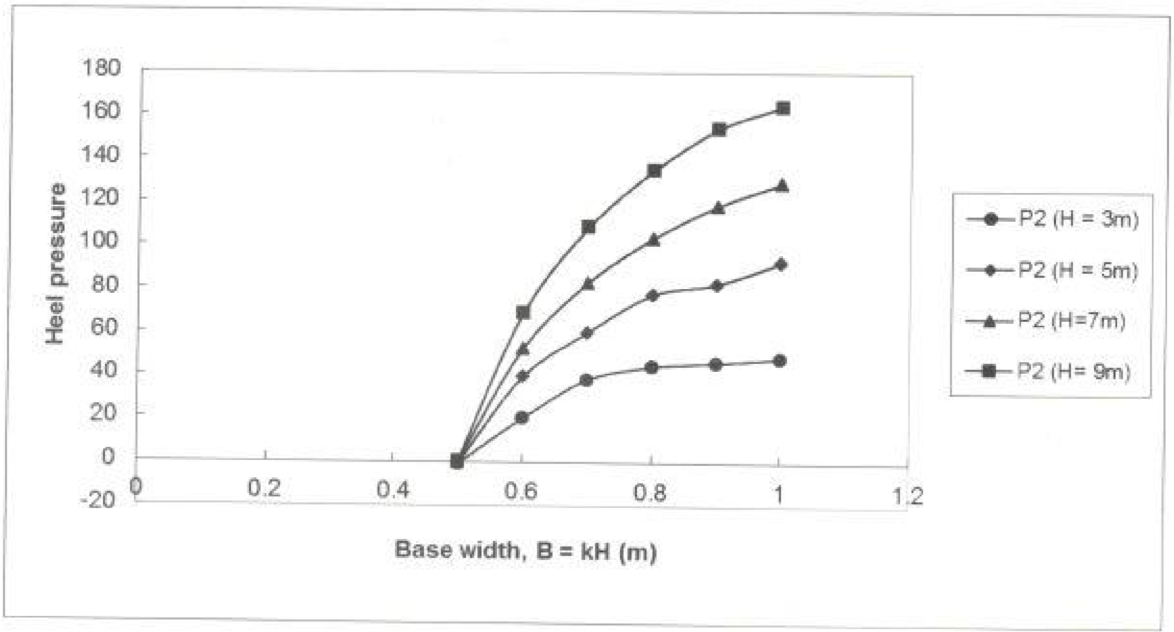

Figure 13: Behaviour of heel pressure against base width for zero surcharge

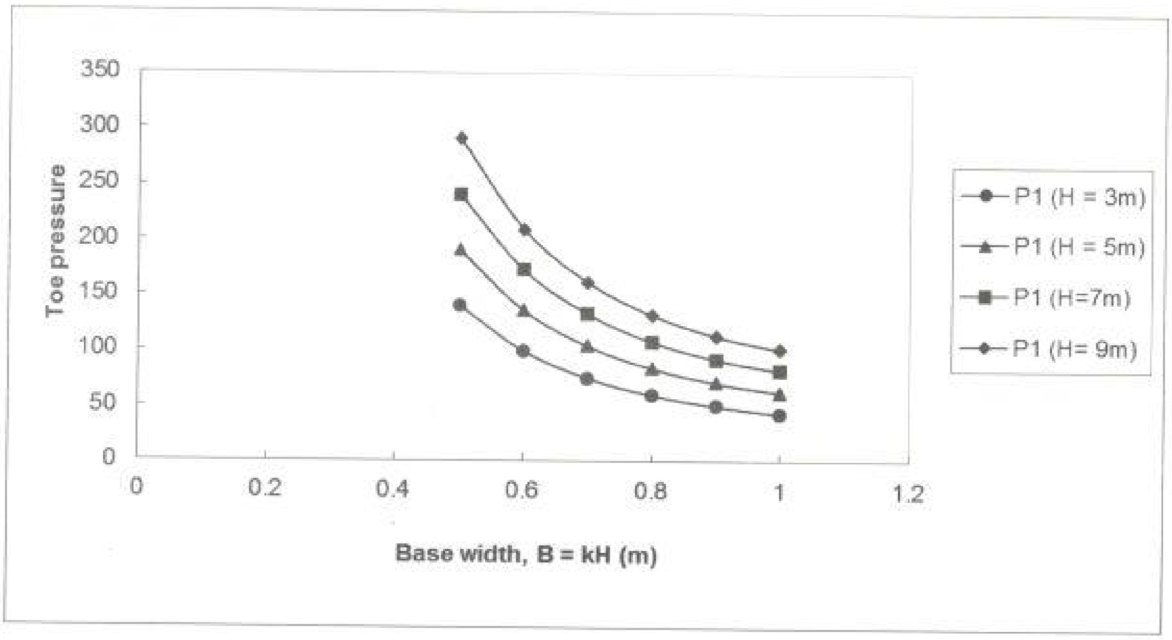

Figure 14: Behaviour of toe pressure against base width for surcharge load of 10 kN/m^2

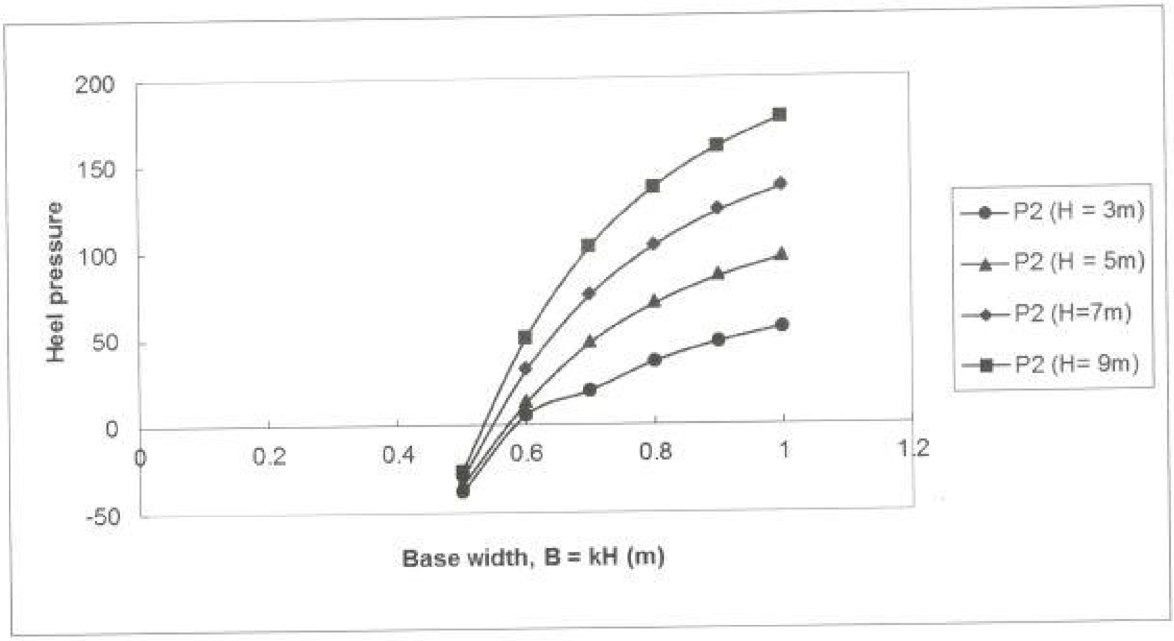

Figure 15: Behaviour of heel pressure against base width for surcharge load of 10 kN/m^2

4.0 CONCLUSION

Resistance offered by retaining wall against sliding increases constantly with constant increase in Base width and increases at an increasing rate with constant increase in height of retaining wall but lateral effect increases at a greater increasing rate. This revealed that higher walls are subjected to severe sliding effect as compared to lower ones. Result also showed that the resistance offered against overturning by the wall increases at an increasing rate with wall height and remains constant for varying base width. This gives an indication that sliding effect is more critical than overturning effect in cantilever retaining walls. This research also shown that an additional (surcharge) Load at the back of retaining walls increase its tendency to failure.

Based on specification given by Raju (2000) about safety factors against sliding (1.5) and overturning (2.0), the dimensions of base width that satisfy this specification are: for walls without surcharge, the dimension of base width is 0.63H which is closed to 0.60H given Raju (2000). 0.70H for wall with surcharge load of 10 kN\m^2, 0.8H for wall with 20kN/m^2 as surcharge load and 0.90H for wall with surcharge of 30kN/m^2. It is also evident that as surcharge load increases, the requirement for sliding, overturning, tension and crushing failures also increases and to satisfy these requirements, the above specified value must be strictly adhered to.

5.0 RECOMMENDATIONS

As it is evident that the tendency to failure of the retaining wall increases with an increase in the load imposed on it, it is very crucial to recommend these values for Base width and other wall dimensions required for satisfactory performance of cantilever retaining wall and also to serve as design aid for different loading conditions. Based on the results of the research carried out, for a cantilever retaining wall without surcharge, the Base width B should be 0.65H. For wall with surcharge load of 10 kN\m^2, the base width, B= 0.7H and B = 0.8H for 20kN/m^2 as surcharge load. Also, for wall with surcharge loads of 30kN/m^2 and 40kN/m^2 the Base widths B should be equal to 0.9H and 1.0H respectively.

Based on these values, the ratios of toe-to-base width and heel-to-base base width are expected to be 0.33 and 0.5 respectively. These values were taken for the worst condition of sliding and, for further increment of surcharge load; the base width must be increased by 0.1 times height of the wall for surcharge load of 10 kN/m^2 increment.

Further research should be carried out to investigate the stability of cantilever retaining wall experiencing the combined effects of submerge soil and surcharge loads

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