THE UNIVERSITY OF ALBERTA

STRESSES IN VERTICAL AND SLOPING CONCRETE CORES of EARTH DAMS

by

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TABLE OF CONTENTS

INTRODUCTION

Stresses and deformations are very important in dam design calculations. The stress analysis is equally important while compared to the stability analysis based on the plastic equilibrium conditions. Two kinds of dam sections have been considered here. The first one is a dam with vertical core and the second one is a dam with sloping core.

The main interest here is to compare the performance of two kinds of concrete cores with respect to their stress distribution. Moreover, it is of interest to observe the behaviour of vertical and sloping concrete cores with respect to the leakage. The leakage will be there due to cracks. Cracks in concrete can be of two types mainly. The first ones are the tension cracks resulting from tensile strains. The second types of cracks are shear cracks resulting from slip action.

In fact, the analysis of stresses is a complex problem but to render the problem tractable some assumptions are to be made. The first of these assumptions is that the actual three-dimensional system can be represented as a two-dimensional plane strain problem. Here the sections are considered normal to the dam axis. The second assumption is that the soil and concrete are both linearly elastic. Now, it is not more than a standard plane strain problem. The third assumption is regarding the loading conditions stating that the dam section has been directly loaded by the gravitational body forces although the actual construction is always carried by incremental loading. The fourth assumption is that the dam foundation is quite rigid.

METHOD OF ANALYSIS

The stress analysis has been carried out by using Finite Element Technique with triangular elements of constant strain. The program used here is the Wilson - Eisenstein version with the automatic generation of nodal points and elements.

The finite element method has been described in many publications and is, in fact, the idealization of an actual elastic continuum as an assemblage of two-dimensional elastic elements, in this case of constant strain. The sections considered are shown in Figures 1-a and 1-b. The mesh arrangement is chosen in such a way that vertical and sloping cores are generated. The nodal points along the foundation contact with soil have been restricted to move horizontally as well as vertically. The dam section has been divided into 220 elements with 132 nodal points. The cycle print interval and output interval used are respectively 5 and 100 cycles and the tolerance limit being equal to 0.1000 E00. The values of modulus of elasticity and density have been taken in terms of KSF and KCF respectively. An overlaxation factor of 1.85 gives quite a satisfactory number of iterations for the solution. The values of modulus of elasticity (E) and Poisson's Ratio (V) of plane stress system were modified to plane strain values of E^* and V^* by using the plane strain analysis.

$$E^* = E/(1-V^2)$$
$$V^* = V/(1-V)$$

The mesh arrangement is shown in Figure 2 and properties of soil and concrete are given in Table 1.

RESULTS

A. STRESS DISTRIBUTION IN VERTICAL AND SLOPING CONCRETE CORES

In order to make a good comparison of the stress distribution, the same quantity of concrete has been used in vertical and sloping cores. The vertical core is 25 feet thick and 100 feet high whereas the sloping core is 9.3 feet thick and 269 feet long, thus each of them giving a concrete quantity of 2500c.feet per foot length of the dam.

The stress contours in the core have been plotted by interpolating between different elemental stresses because of the non-reliability of stresses existing at the nodal points due to the presence of the interface between the concrete and the soil. Moreover the bottom-most stresses have been neglected due to their nearness to the boundary.

(i) Distribution of Horizontal and Vertical Normal Stresses

The magnitude of the horizontal and vertical normal stresses in case of vertical concrete core is found to be far greater as compared to the magnitude of horizontal and vertical normal stresses existing in the sloping còre. The foundation contact of the dam along the dam axis is under quite higher vertical normal stresses but under quite lower horizontal normal stresses in case of a dam with vertical core as compared to the one with sloping core. The core interface with foundation is under quite higher horizontal and vertical normal stresses in case of vertical core as compared to the horizontal and vertical normal stresses in case of sloping core. This distribution is shown in Figures 3 and 4.

The horizontal normal stresses in the vertical core are nearly twice as much as the horizontal normal stresses existing in the sloping core but the maximum vertical normal stress in vertical core is about ten times the maximum vertical normal stress in the sloping core.

(ii) Distribution of Principal Stresses

The magnitude of the principal stresses is far greater in vertical core as compared to the one in sloping core. Also, the direction of maximum and minimum principal stresses in both types of cores is totally different but still there is one kind of similarity regarding the direction of the principal stresses as compared to the slope of vertical and sloping cores. The direction of maximum principal stresses is nearly parallel to the vertical interface of the core with the soil, and the direction of minimum principal stresses is nearly horizontal in case of vertical concrete core but the direction of maximum principal stresses is nearly parallel to the direction of the sloping core and the direction of minimum principal stresses deviates not much from the normal direction to the direction of the sloping core in case of a sloping concrete core. The magnitude and direction of the principal stresses also verifies the idea expressed by Sherard that the foundation contact moves u/s in case of sloping core but the vertical core is quite free from this type of movement. Had the direction of maximum principal stresses in sloping core been vertical, which is not possible in this case, there was quite little possibility of the movement of the foundation contact of core. From the analysis, it is quite clear that no tensile stresses have been found, so no tensile strains would be expected in both types of cores. The stresses and strains present here are the compressive ones only. This stress distribution is shown in Figure 5.

(iii) Distribution of Maximum Shear Stresses

Maximum shear stress distribution is shown in Figure 6. The vertical core is found to be under quite higher shear stresses as compared to the sloping core. The maximum value of shear stress in vertical core is found to be 4.96 Kips/sq. ft. but maximum shear stress in sloping core is about 1.0 Kip/sq. ft. This would be expected because of the higher magnitude of maximum principal stresses and lower magnitude of the minimum principal stresses in vertical core as compared to the sloping core. Since the maximum shear stress is just one half of the difference between the maximum and minimum principal stresses, therefore, the magnitude of maximum shear stresses is quite higher in case of vertical core as compared to the sloping core. The direction of the maximum shear stress can also be obtained if refered to Figure 5 in which the direction of principal stresses is shown. Since the maximum shear stress direction is always 45^o away from the direction of principal stresses, therefore, the direction of maximum shear stresses is also known.

(iv) Distribution of Horizontal Shear Stresses

Refering to Figure 7, the magnitude of horizontal shear stresses in sloping core is far greater as compared to the magnitude of horizontal shear stresses existing in vertical core. The maximum shear stress in vertical core is 0.24 KSF whereas the maximum shear stress in sloping core is a little higher than 0.80 KSF.

B. COMPARISON OF HORIZONTAL AND MAXIMUM SHEAR STRESSES IN VERTICAL AND SLOPING CORES.

Refering to Figures 6 and 7, the vertical core is very heavily loaded by the maximum shear stresses as compared to the horizontal shear stresses. The maximum values of shear stresses are nearly ten to fifteen times the horizontal shear stresses. The horizontal shear stresses are lower because the Poisson's Ratio is lower in case of concrete but the maximum shear stress is higher because of the large difference between the values of maximum and minimum principal stresses. While in case of sloping core there is not much difference between the horizontal and maximum shear stress values because the difference between maximum and minimum principal stresses is not much higher as compared to the stress difference with respect to the principal stress values existing in the vertical core.

C. POSSIBILITY OF CRACKING OF VERTICAL AND SLOPING CONCRETE CORES

Two types of cracks may appear in vertical and sloping cores. The first ones are the tension cracks and the second ones are shear cracks.

(i) Tension Cracks:-

Tension cracks result from the tensile strains which are in fact due to the tensile stresses. Since no tensile stresses have been found in the above analysis in vertical and sloping cores, there are no tensile strains and hence there is not any possibility of tension cracks.

(ii) Shear Cracks:-

Shear cracks result from shear strains caused by shear stresses. Even the slips between particles will cause microcracking of the concrete if the concrete mix is not properly graded and is non-homogeneous. The sloping core is not under so high values of shear stresses as compared to the vertical core. But if shear cracking occurs it will occur in vertical core. Since the maximum shear stresses in vertical core are still quite lower than the ultimate stresses in concrete, shear cracking will be of microcracking type.

In conclusion, if a choice has to be made of vertical or sloping core with respect to leakage caused through the cracks, the sloping core will be less inclined to all kinds of cracks. Moreover, sloping core would be placed after the whole embankment fill has been placed. Anyhow, this analysis prefers the use of sloping concrete core as compared to vertical core.

D. THE EFFECT OF VERTICAL AND SLOPING CORES ON THE NORMAL STRESSES AND HORIZONTAL SHEAR STRESSES EXISTING IN HOMOGENEOUS SECTION OF THE DAM HAVING THE SAME VOLUME.

The stress contours are available in Figures 3, 4 and 7 for both the dam sections.

The vertical core increases the values of σ_Y stresses at the core interfaces. This is the reason why the vertical normal stress (σ_Y) contours get a sudden jump near the interface of soil with concrete. On the other hand, vertical core wall reduces the horizontal normal stresses (σ_X) at the foundation interface and increases the vertical normal stress (σ_Y) over-there. There is also a lateral and downward shift of the shear stress contours away from vertical core interfaces with the soil, thus, resulting in reduction of the shear stress values in the soil. The increase in value of vertical normal stress at the foundation interface is quite helpful against the seepage through the foundation contact with the core-wall.

In the case of an upstream sloping concrete membrane, the horizontal normal stress contours are shifted towards the sloping core thereby increasing the horizontal normal stress (σ_X) values on the lower one-third portion of the membrane quite significantly. The vertical normal stress contours are also shifted laterally towards the sloping membrane. This results in increasing the values of σ_Y at membrane interface with the soil.

The most significant thing is that the upstream membrane attracts the shear stress contours towards itself, thereby increasing the shear stress values nearly at the one-half portion of the sloping membrane. The heel and toe portion of the sloping core are under heavier shear stresses as compared to the state of shear stress existing in the homogeneous section of the dam without core. In practice, while bonding the end of the sloping core with the foundation, proper contact area should be provided in order to prevent any kind of damage against shear stresses at core interface with the foundation.

CONCLUSIONS

The stress analysis carried out with the finite element technique results in concluding the following major points in cases of vertical and sloping concrete cores.

(1) The vertical concrete core is under higher values of maximum shear stresses but under lower values of horizontal shear stresses as compared to the sloping core.

(2) The vertical concrete core is under higher values of horizontal and vertical normal stresses while compared to the sloping concrete core.

(3) Since no tensile stresses have been found in vertical and sloping cores, there is not any possibility of tension cracks.

(4) Micro-shear cracking in vertical core can cause leakage through the core, whereas the sloping core is more free from all kinds of cracks. Therefore, the use of sloping core with respect to leakage is prefered.

(5) The stress analysis also confirms the general idea that the dams with vertical concrete cores give higher pressures on the contact between the core and the foundation. This provides more protection against the possibility of any leakage along that contact.

(6) The foundation contact area of the sloping core needs careful bonding of the concrete with the foundation because the lower portion of the upstream membrane is under higher maximum and horizontal shear stresses as compared to the upper portion of the membrane.

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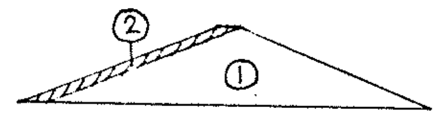
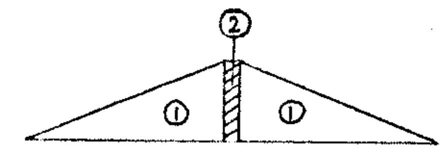


DAM WITH SLOPING CONCRETE CORE



DAM WITH VERTICAL CONCRETE CORE

MATERIAL	NO.	PLANE STRESS			PLANE STRAIN		
		DENSITY (Kcf) γ	POISSON'S RATIO ν	MODULUS OF ELASTICITY E (ksf)	DENSITY (Kcf) γ	POISSON'S RATIO ν	MODULUS OF ELASTICITY E (ksf)
SAND AND GRAVEL	①	0.135	0.400	200	0.135	0.667	238
CONCRETE	②	0.150	0.200	400	0.150	0.250	417

TABLE 1 PROPERTIES OF MATERIALS

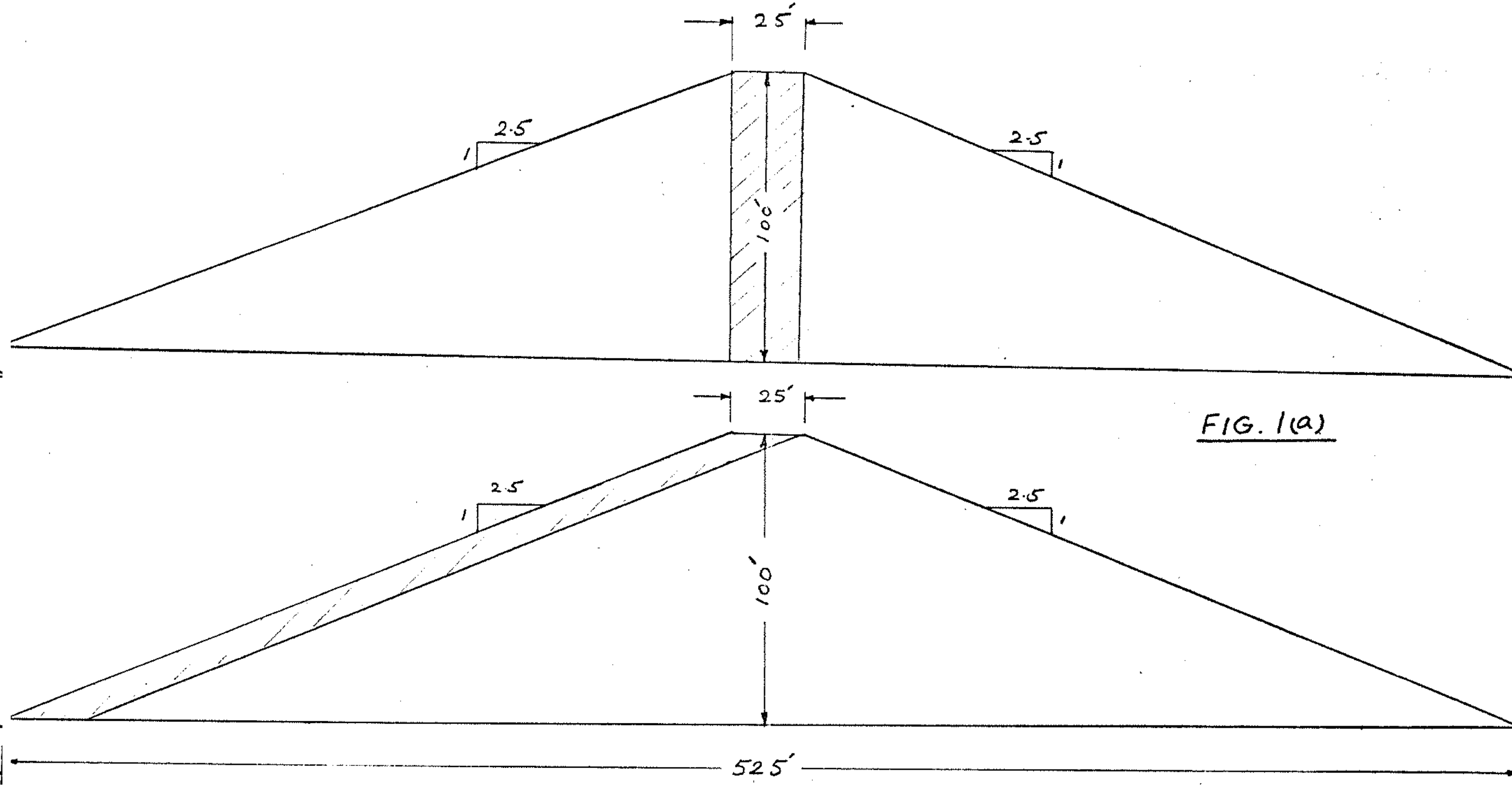


FIGURE 1 DAM SECTIONS

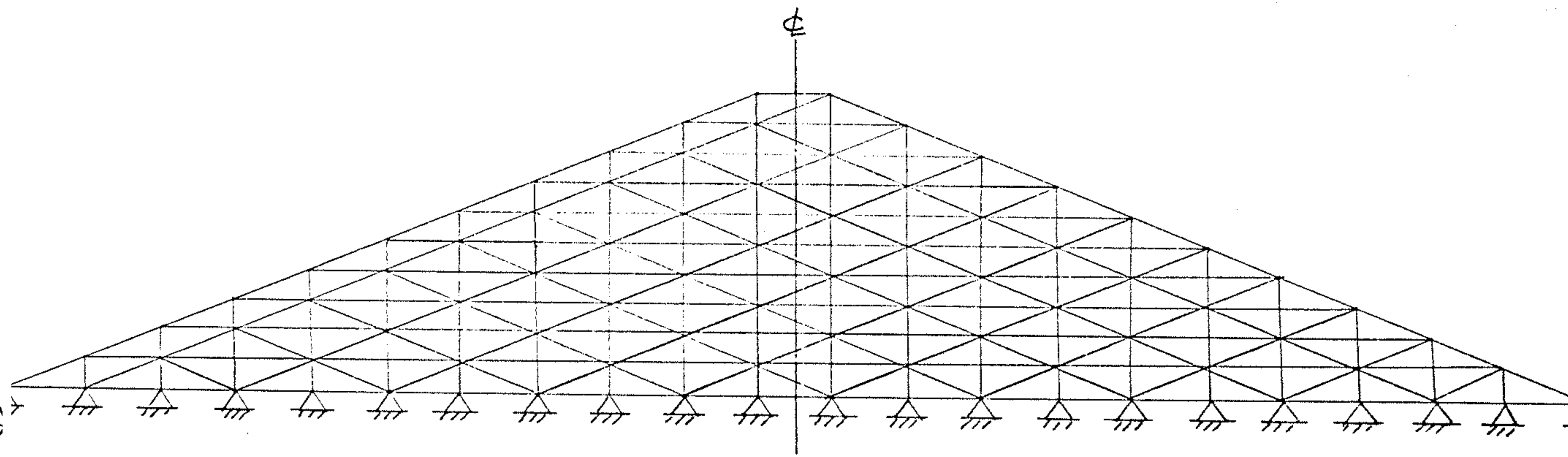


FIGURE 2 FINITE ELEMENT IDEALISATION OF EARTH DAM

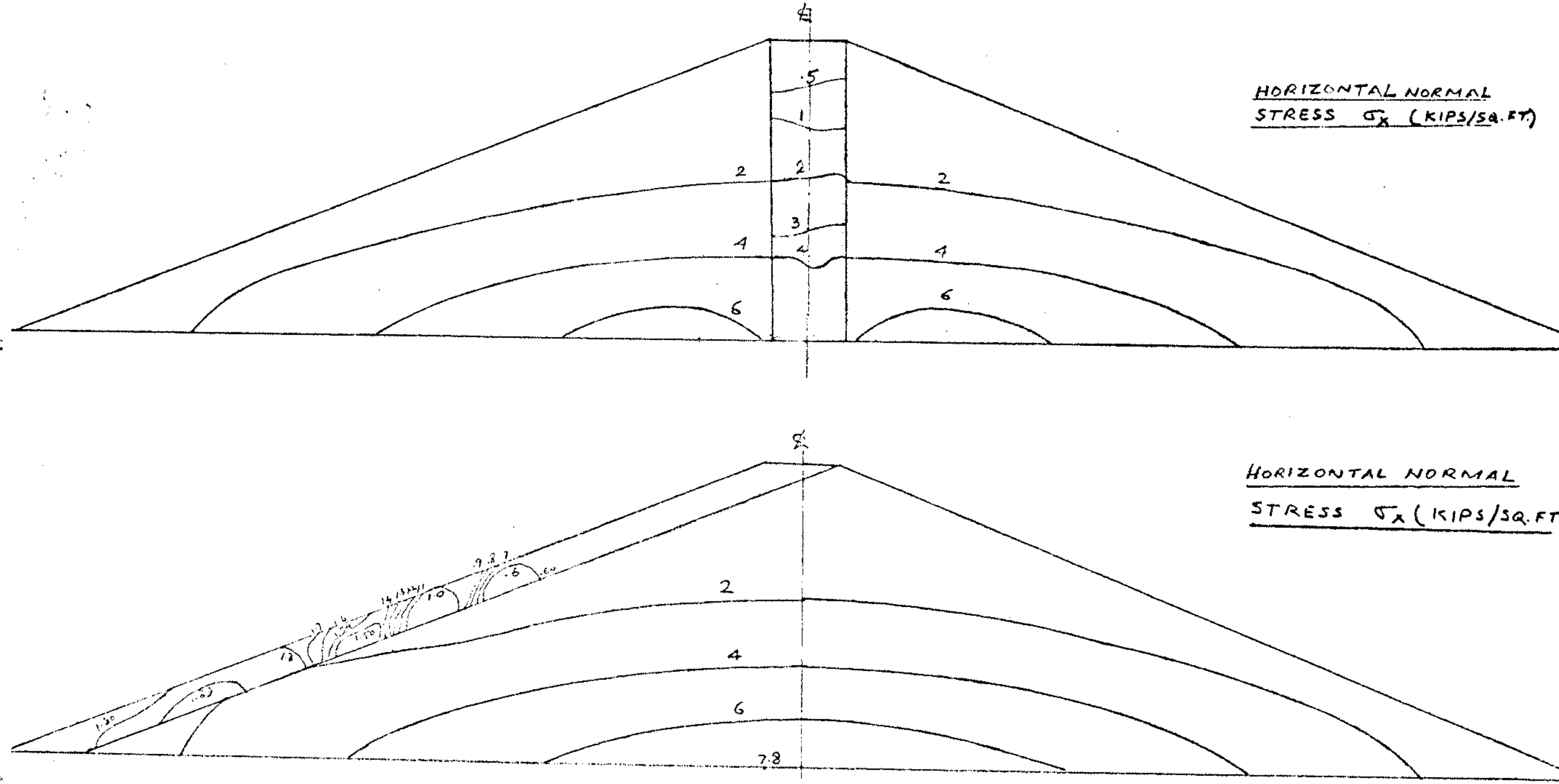


FIGURE 3 DISTRIBUTION OF HORIZONTAL NORMAL STRESSES

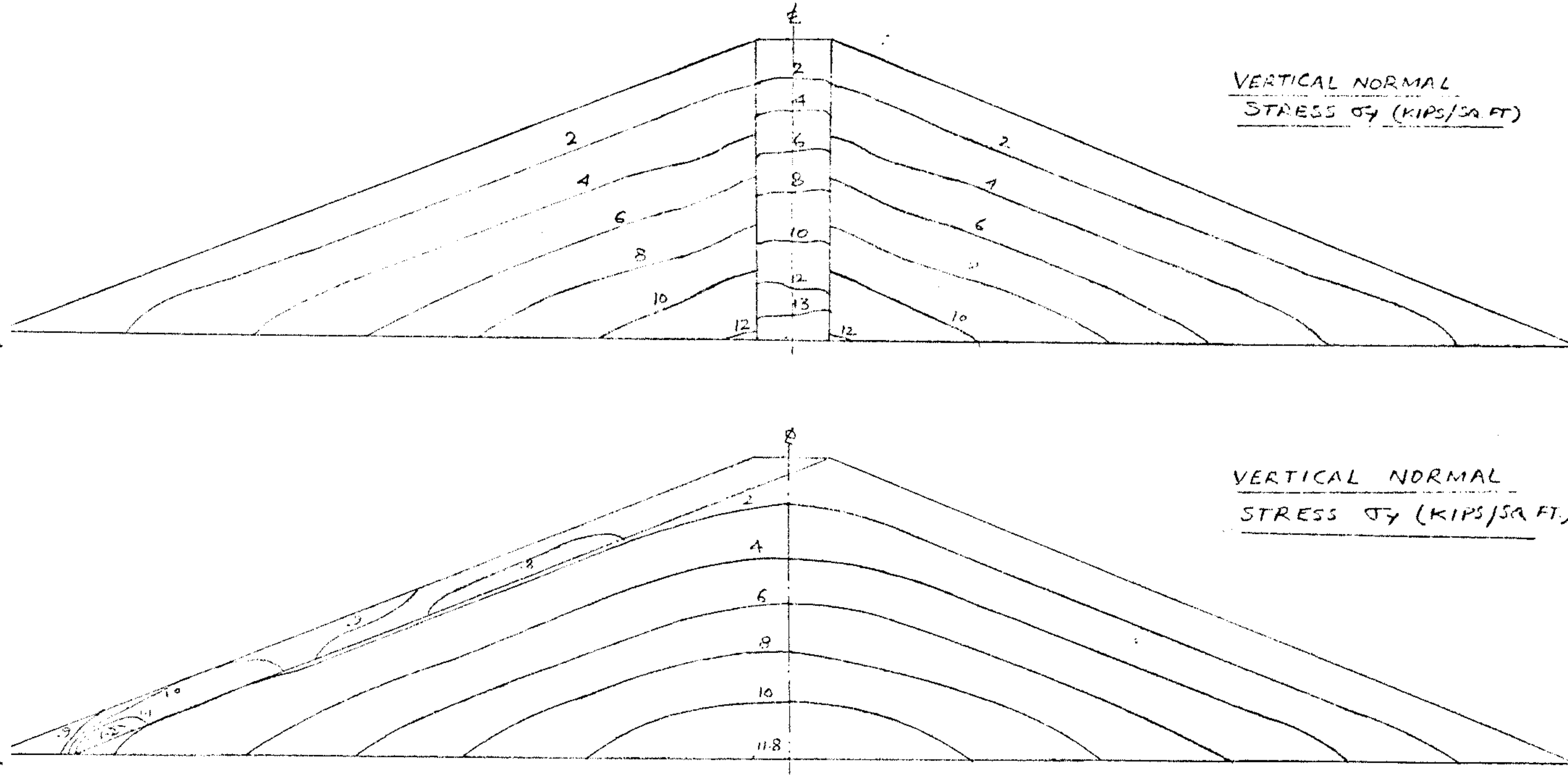


FIGURE 4 DISTRIBUTION OF VERTICAL NORMAL STRESSES

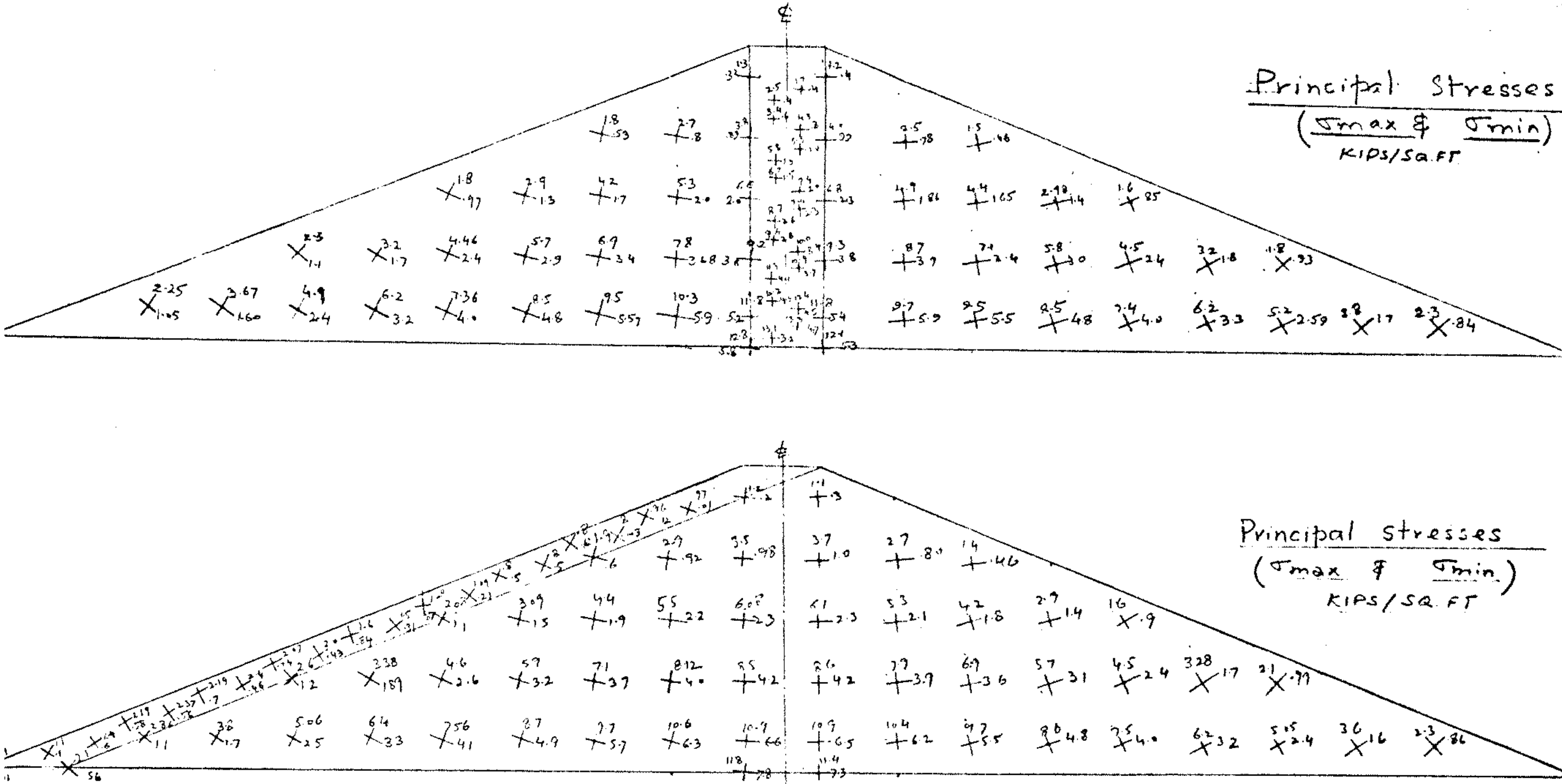


FIGURE 5 DISTRIBUTION OF PRINCIPAL STRESSES

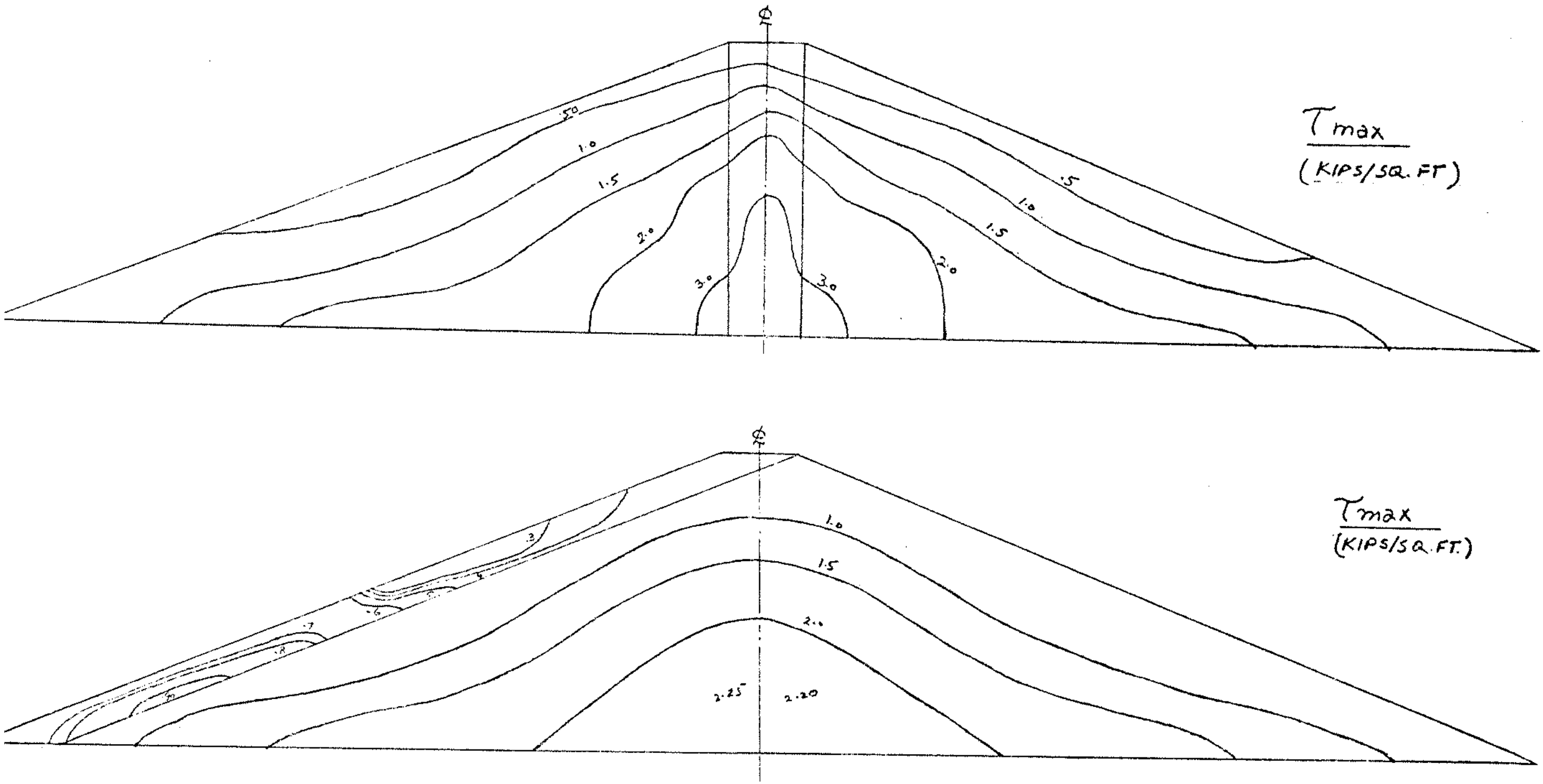


FIGURE 6 DISTRIBUTION OF MAXIMUM SHEAR STRESSES

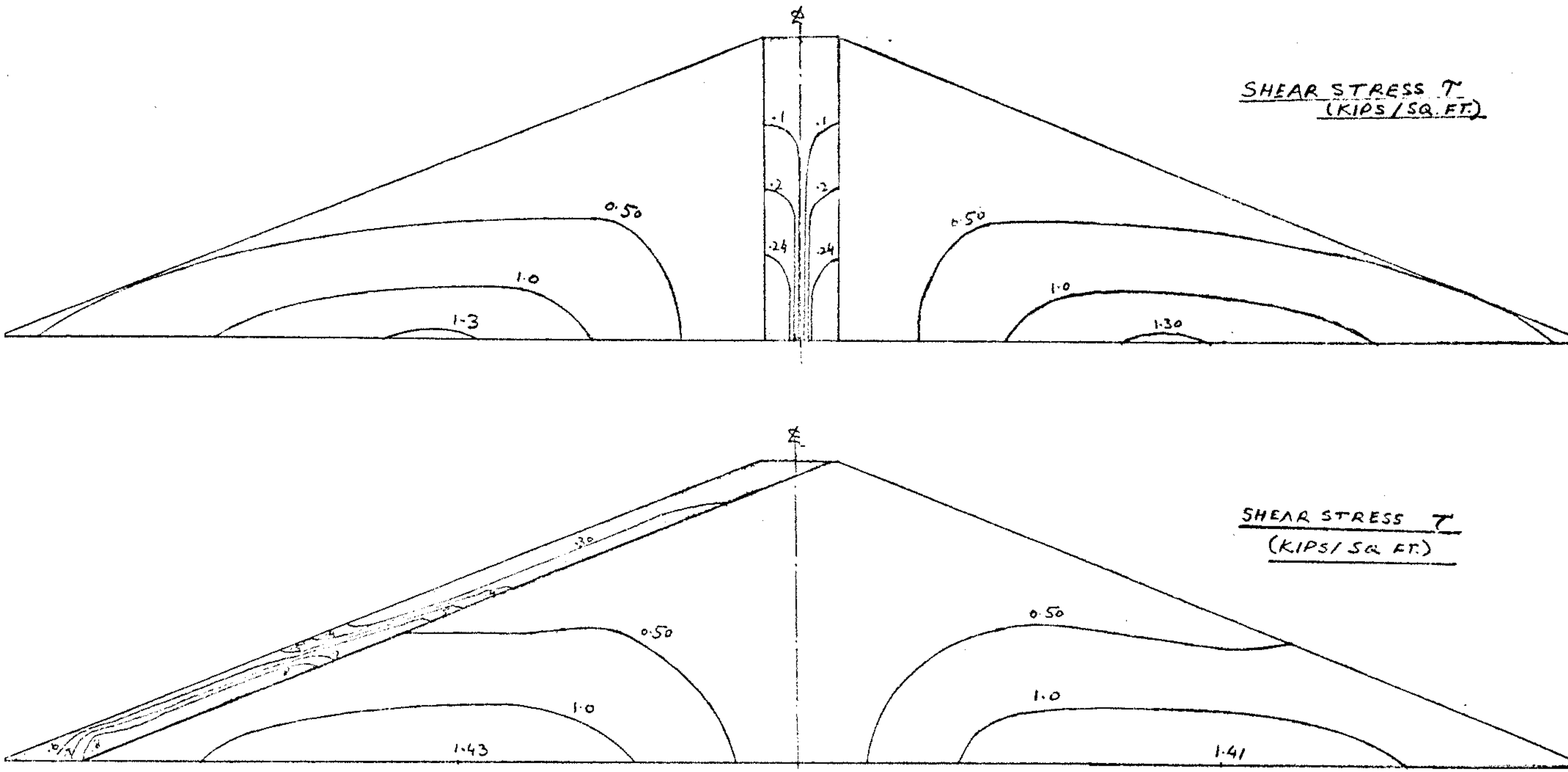


FIGURE 7 DISTRIBUTION OF HORIZONTAL SHEAR STRESSES