Soil Structure Interaction of Well Foundations Model Studies

by

R.K. Katti*

S.D. Deokule**

J.N. Vyas**

Introduction

WITH increase in industrialization in India a large network of Highways and Railways is under construction. A large number of bridges have to be constructed to cross over various rivers all over the country. In majority of the cases the bridges have to be built in alluvial deposits wherein the depth of the overburden soil is quite high. In view of this use of well foundations for the construction of bridges across the rivers has become a common feature.

Though well foundations have been used since long by bridge builders still there is no proper theoretical and design concepts available for the design of well foundations, specially with reference to lateral forces shared by the soil around the sides and that at the base of the well foundations. The problem as such is of the statically indeterminate nature. Formerly some attempts were made by engineers and research workers to evaluate the nature of active pressure and passive resistance offered by the soil around the well foundation (Terzaghi 1943, Pender 1947, Menard 1962). All these theories were based on some assumptions.

However, it is observed that there is no definite method available to assess the moments and the stresses shared by the soils around the sides and the base of the well foundation subjected to lateral pull. This is necessary for the design of grip length. Recently some model tests were carried out by Sankaran and Murthy (Sankaran 1969). Even in these model tests an attempt was made to calculate pressure mobilized by certain assumptions in relation to rotational aspects of the well.

To actually ascertain the nature of pressure distribution around the well foundation various lateral load conditions model tests have been carried out by mounting pressure cells both on the sides as well as at the bottom.

Two types of model tests were conducted :

(*i*) Small size model test; and

(*ii*) Large size model test.

---

* Professor of Civil Engg. (Soil Engg.), Indian Institute of Technology, Bombay.

** Postgraduate Students in Soil Engg., Indian Institute of Technology, Bombay.

This paper was received on 23 March 1971. It is open for discussion up to July 1972.

Experimental Set-up

For convenience of presentation and analysis the work conducted on Small Scale and Large Scale types is presented under headings part A and Part B.

PART A : SMALL SCALE MODEL TEST

Well Model=0·22 m×0·2 m×0·9 m high well model was fabricated from 1·87 cm thick M.S. Plate with threaded holes for mounting 5 cm diameter pressure cells as shown in Figure 1.

Tank : The tank has inside dimensions 2·7 m×0·9 m×0·9 m high.

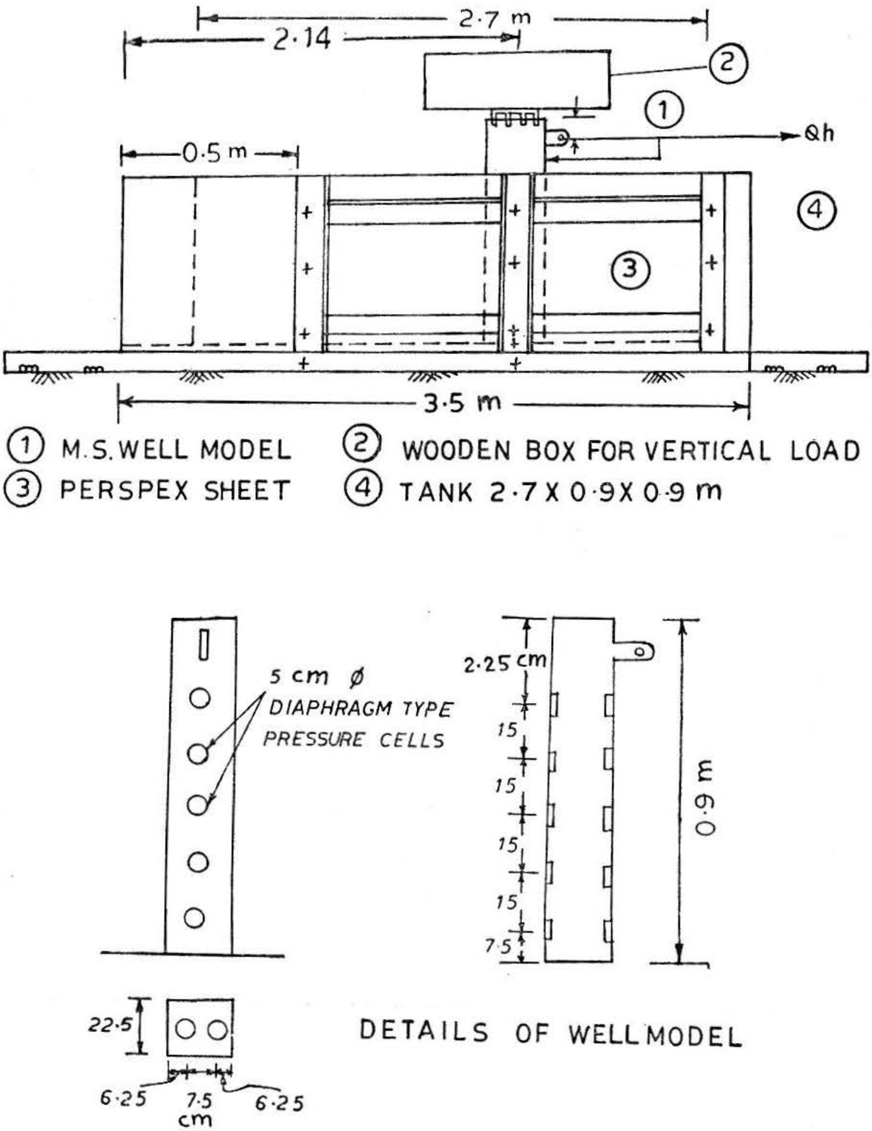


FIGURE 1 : Showing experimental set-up for small size model test.

These dimensions were fixed by taking into consideration the dimensions of the well model.

Vertical Load Arrangement : Application of vertical load is done by a wooden box filled with iron weights and fixed to the model.

Horizontal Load : Horizontal load was applied with the aid of pulley arrangement and dead load as shown in Figure 1.

Procedure for Testing

In these tests sand was used as a soil material. Soil layer of 22·5 cm thickness was compacted through proper compactive efforts to achieve a uniform density of 1·62 gm/cc. Well model weighing 90 kg was kept in vertical position at the centre of the tank. The external vertical load of 100 kg was placed in box which gave a combined pressure intensity of 0·43 kg/m² at the base. Pressure cell reading was recorded.

Required amount of sand was compacted around the well to achieve a uniform density of 1·62 gm/cc. Required amount is dependent on d/b ratio to be studied.

Dial-gauges were fixed along the sides to know the tilt and the initial readings were taken. Horizontal load was now applied in small increments till failure.

Pressure readings obtained by the pressure cells at sides as well as at the base were recorded.

Dial-gauge readings were also recorded and tests were carried out till failure. The d/b ratios studied are 0, 1·5, 1·75, 2 and 2·5.

PART B : LARGE SCALE MODEL TEST

1·22 m × 0·95 m × 5·5 m high well model was fabricated from M.S. angle sections and 0·6 cm thick aluminium sheets 7·5 cm diameter pressure cells were mounted on this with the aid of 10 cm × 10 cm. M.S. plates having projection equal to the thickness of the aluminium sheets and screwed to the sheet so that the shell flushes with the outside (Figure 2). Brick lining was put inside the model to prevent flexibility. Rest of the space was filled with sand and iron pieces.

Multipurpose Soil Testing Bed (M.S.T.B.) has reinforced concrete container. The container is 6 m long, 3 m wide and 5 m deep. Steel frames are provided at 3 m c/c projecting out. Each of these frames is able to take 100 tonnes loading. With the help of bulk head attached to the frames it is possible to increase the depth by another three metres.

Vertical Load Arrangement : Vertical load was placed directly into the hollow space of the well model and the remaining space was filled by the sand.

Horizontal Load : Horizontal load was applied by wire and pulley arrangement as shown in Figure 2.

Testing Procedure

Initial 1 m sand layer was compacted in 22·5 cm layers to attain a uniform density of 1·62 cm, then well model was placed into vertical position at the centre of the M.S.T.B. and dead load was placed which gave a combined intensity of pressure of 0·83 kg/cm² at the base. Dial-

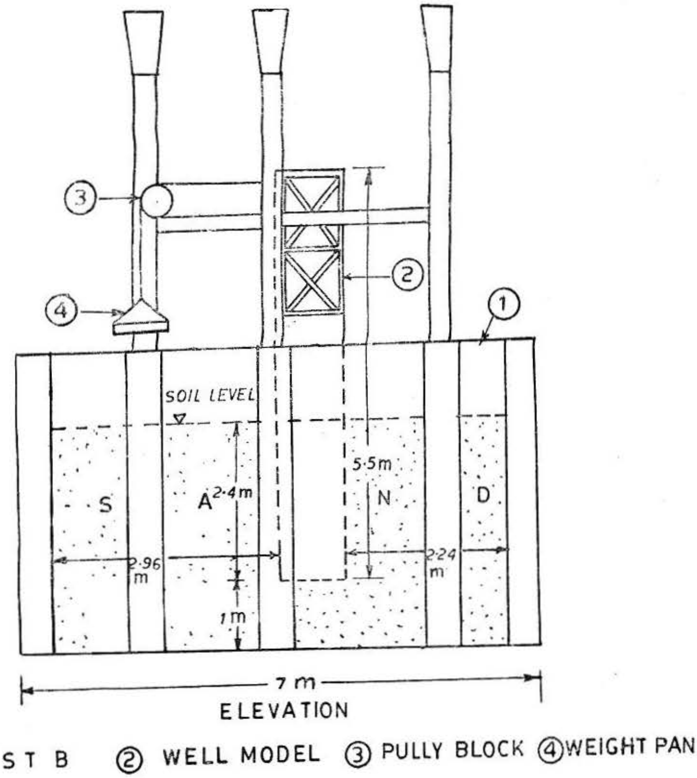


FIGURE 2 : Showing experimental set-up for large size model test.

gauges were mounted at three different positions to measure deflection of the axis. Sand was compacted in 22·5 cm layers up to 2·14 m around the well model to attain a uniform density of 1·62 gm/cc.

Horizontal load was applied in increments of 100 kg up to 1·4 tonnes and pressure cells as well as dial-gauge observations were taken for each increment.

Horizontal load was then decreased in steps of 200 kg and every time the pressure cells and dial-gauge readings were taken.

Analysis of Data

PART A : SMALL SCALE TEST

Prior to organizing the various tests nature of forces expected to develop between the well foundation and the soil under idealized condition were visualised. These forces are shown in Figure 3.

The nature of forces clearly indicates that the force system is statically indeterminate in nature. However, an examination of the system indicates that the various forces developed may be correlated to the deformation characteristics of the soil mass and nature of rotation of the well and base, *etc.*

To avoid interference action, the number of pressure cells mounted have to be limited both at the base and at the sides. The observations

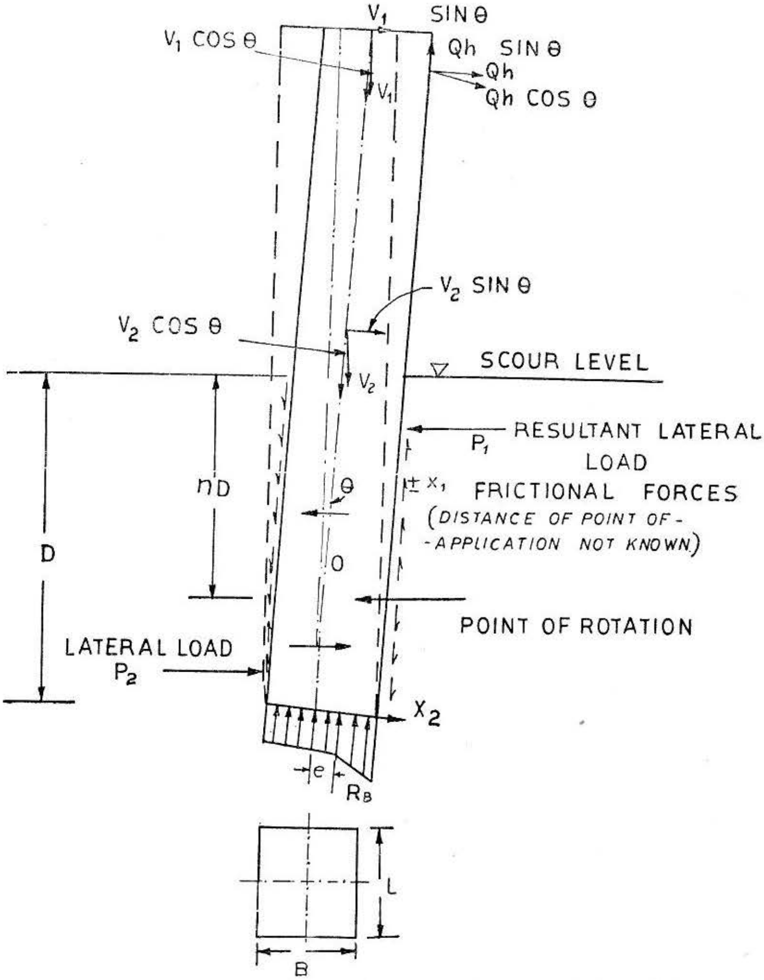


FIGURE 3 : Showing idealized force system around the model.

of the pressure cells would give average nature of pressure distribution in that region. With the help of the pressure cell reading an attempt is made to visualize the nature of stress distribution at the bottom and sides of the well. As a first step it is necessary to evaluate the pattern of pressure distribution under the base at zero embedment with the application of certain lateral loads. This would help in assessing the pattern of stress distribution at the base. For subsequent studies with various embedments for evaluating the moments and the stresses taken by the base, the pattern of stresses evaluated in the first test would be utilized. The change, however, would be in the magnitude.

For a well to be in equilibrium under a given vertical and lateral loads it should satisfy the following three criterion, *viz.*

$$\Sigma V=0, \Sigma H=0, \Sigma M=0.$$

All the three parameters would be zero only when a very accurate stress distribution between well and the soil media is evaluated. In the present analysis the patterns of stress distribution at the bottom and sides are evaluated. For each case moment shared by the sides and the base and *kv* and *kh* values are evaluated. Further an attempt is made to see the variation with reference to non-dimensional parameters such as $\frac{d}{b}$ ratio, θ, *etc.* For clarity two cases have been presented to illustrate method of evaluating pattern of stress distribution, point of rotation. *etc.* The results are discussed later.

Case I : $\frac{d}{b}=0 \quad Qn=2$ kg

(*i*) Vertical weight consists of self weight of the well V_2 = 90 kg
External vertical load V_1 = 100 kg

(*ii*) Horizontal pull Qh = 2 kg

(*iii*) Pressure recorded on pressure cells = $P_{11}=0{\cdot}36$ kg/cm²; $P_{12}=0{\cdot}40$ kg/cm²

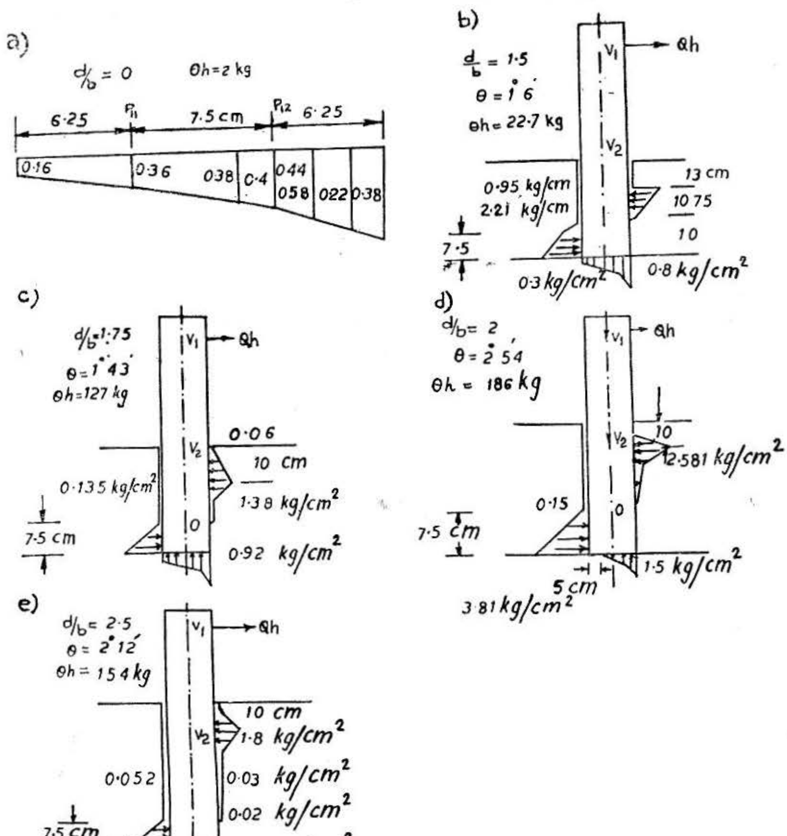


FIGURE 4(a to e) : Showing pressure distribution patterns obtained for (a) $\frac{d}{b}=0$, (b) $\frac{d}{b}=1{\cdot}5$, (c) $\frac{d}{b}=1.75$, (d) $\frac{d}{b}=2$ and (e) $\frac{d}{b}=2{\cdot}5$.

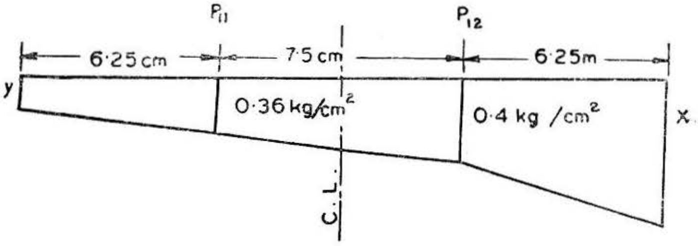
(*iv*) Tilt $\theta=1° 11'$

From Figure 4 (*a*)

$\Sigma V=V_1 \text{ Cos } \theta+V_2 \text{ Cos } \theta-Qh \text{ Sine } \theta=190$ kg

$\Sigma H=V_1 \text{ Sin } \theta+V_2 \text{ Sin } \theta+Qh \text{ Cos } \theta \quad =5{\cdot}92$ kg

$\Sigma M=V_1 \text{ Sin } \theta\times d_1+V_2 \text{ Sin } \theta\times d_2+Qh \text{ Sin } \theta\times d_3$
$+Qh \text{ Cos } \theta\times d_4 =435{\cdot}5$ kg/cm.



Taking pressure cell readings at the base valid and assuming the pattern as shown in figure working out the x and y ordinates by comparing ΣV and ΣM developed at the base

$$\frac{0{\cdot}36+y}{2}\times 6{\cdot}25\times 22{\cdot}5+7{\cdot}5\left(\frac{0{\cdot}36+0{\cdot}4}{2}\right)\times 22{\cdot}5+$$

$$\frac{0{\cdot}4+x}{2}\times 6{\cdot}25\times 22{\cdot}5=190 \qquad ...(A)$$

Now taking the moments around the centre or rotation

$$y\times 6{\cdot}25\times 22{\cdot}5\,(6{\cdot}87)+\frac{0{\cdot}36-y}{2}\times 6{\cdot}25\times 22{\cdot}5\times 5{\cdot}83$$

$$-\frac{0{\cdot}04}{2}\times 7{\cdot}5\times 22{\cdot}5\times 1{\cdot}25-0{\cdot}4\times 6{\cdot}25\times 22{\cdot}5\times 6{\cdot}87$$

$$-\left(\frac{x-0{\cdot}4}{2}\right)\times 6{\cdot}25\times 22{\cdot}5\times 7{\cdot}92=-435{\cdot}5 \qquad ...(B)$$

Solving Equations (*A*) and (*B*)

We get $x=0{\cdot}88$ kg/cm² and

$y=0{\cdot}16$ kg/cm²

Hence, the pressure distribution pattern is fixed putting the values of x and y.

Value of $\phi_d=1° 11'$ under the effect of horizontal load. Base of the well will undergo same tilt as it is rigid. Due to this pressing against soil under the effect of horizontal load tangential frictional force is developed which can be formulated in the relationship as

$V \tan \phi_d=H$, where H=Horizontal pull and V=Vertical load acting normal to the surface

$$\tan \phi_d=\frac{H}{V}=\frac{5{\cdot}92}{190}=0{\cdot}032$$

$\therefore \quad \phi_d=1° 52' << 31°$ (ϕ critical)

Value of Kv—

Kv=Coefficient of vertical subgrade reaction $= P_v/\delta_v$,

where

δ_v=Deflection at the point. Values of Kv at every 2 cm distance from centre towards the edge on the side of horizontal load is worked cut and tabulated in Table I.

TABLE I

Lateral load	Distance from centre to the base	Settlement δ_v (cm)	$P_v\left(\frac{kg}{cm^2}\right)$	$Kv=\frac{P_v}{\delta_v}$
2 kg $\theta=1°11'$	2	0·0414	0·38	9·2
	4	0·0828	0·44	5·3
	6	0·1242	0·58	4·67
	8	0·1656	0·72	4·35
	10	0·204	0·88	4·40
2·5 kg $\theta=2°38'$	2	0·092	0·47	5·1
	4	0·184	0·56	3·04
	6	0·276	0·72	2·6
	8	0·368	0·92	2·5
	10	0·460	1·08	2·35

Failure load=4 kg.

Case II : $d/b=1{\cdot}5$

Here the well model is embedded to a depth equal to 1·56. The percentage moments shared by soils around the sides of the well and that at the base is not known. In view of this to evaluate the moment taken up by the base the pattern of stress distribution assumed is similar to one obtained under case $d/b=0$. The magnitudes, however, differ depending upon the pressures observed on the base pressure cells. The residual moment is balanced against sides to be within ± 5 percent of the accuracy. Results are presented below:—

(1) Lateral pull $Qh=22{\cdot}7$ kg

(2) Vertical load V consists of

(*i*) External Vertical Load V_1 =100 kg

(*ii*) Self weight V_2 of the model = 90 kg

(3) Pressure recorded on pressure cells

$P_{11}=0{\cdot}32$ kg/cm² $P_{12}=0{\cdot}38$ kg/cm²

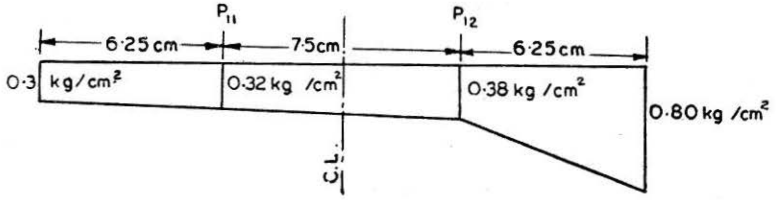
(4) Tilt $\theta=1°\,6'$

(5) Settlements 1, 2, 3, 4, and 5 worked out at 2, 4, 6, 8 and 10 cm from the centre towards the edge of the base are 0·0384, 0·0768, 0·1152, 0·1536 and 0·1920 cm respectively.

(6) Values of Kv_1, Kv_2, Kv_3, Kv_4, and Kv_5 selected from Table I are 9·2, 5·3, 4·67, 4·35 and 4·2 kg/cm³ respectively.

(7) Pressures calculated from the known values of Kv and δ_v at corresponding points are 0·35, 0·40, 0·537, 0·68 and 0·80 kg/cm² respectively.

Hence, the pressure distribution at the base will be :—



(8) $\Sigma v = v_1 \text{Cos}\ \theta + v_2 \text{Cos}\ \theta - Qh \text{Sin}\ \theta = 189{\cdot}53$ kg

Σv balanced by the base

$$=(0{\cdot}30\times20\times22{\cdot}5)+\left(\frac{0{\cdot}1\times13{\cdot}75}{2}\right)\times22{\cdot}5+\left(\frac{0{\cdot}1+0{\cdot}5}{2}\right)\times 6{\cdot}25\times22{\cdot}5=190{\cdot}63 \text{ kg}$$

(9) $\Sigma H = v_1 \text{Sin}\ \theta + v_2 \text{Sin}\ \theta + \text{Cos}\ \theta = 1{\cdot}92 + 1{\cdot}72 + 22{\cdot}7 = 26{\cdot}34$ kg

(10) Position of point of rotation above base=8·4 cm

(11) Moment balanced by base=238 kg cm.

(12) Total moment about $0 = v_1 \text{Sin}\ \theta\ d_1 + v_2\ \text{Sin}\ \theta\ d_2 + Qh\ \text{Sin}\ \theta\ d_3 + Qh\ \text{Cos}\ \theta\ d_4 = 1{\cdot}92\times82 + 1{\cdot}73\times37 + 0{\cdot}435\times10 + 22{\cdot}7\times75$
$= 1985$ kg cm

(13) ∴ Residual moment=1985−238=1747 kg cm

(14) Moment to be balanced by sides=1747 kg cm.

In order to satisfy the conditions of static equilibrium this residual moment should be balanced by resisting moment developed along the sides. Taking pressure cell readings along the sides valid and assuming the pressure at soil surface as very near to zero the probable pattern of pressure distribution is obtained and an attempt is made to see that it balances the residual moment as well as the horizontal pull reasonably [Figure 4 *(b)*].

PART B : LARGE SCALE MODEL TEST

Here in this case same mode of approach was followed. Base pressure distribution diagram was finalised first by fitting method taking into account that $\Sigma v = 0$. From this moment shared by base was worked out and the residual moment was balanced against sides to be within ± 5 percent accuracy.

The results of this test are tabulated in Table II.

Discussion of Results

By approaching the analysis in a step by step fashion it was possible to ascertain to some extent the moments shared by the soil around the sides of the well and at the base, change in position of point of rotation with angle of tilt of the well under various lateral loads and Kh and Kv values for various conditions.

It is observed from the data that for a given embedment with increase in lateral load the tilt goes on increasing and secondly, the position of point of rotation also goes on increasing, *e.g.*, this increase as can be seen from Table III is from 1° 6′ for 22·7 kg lateral load to 2° 42′ for 66 kg lateral load for $d/b=1{\cdot}5$.

The change in position of point of rotation with the angle for a given $\frac{d}{b}$ value is a straight line variation as may be seen from Figure 5. As $\frac{d}{b}$ ratio increases for a given value of θ the point of rotation decreases with respect to base, *i.e.*, the point of rotation shifts towards the base with increasing value of $\frac{d}{b}$ for a particular value of tilt, *i.e.*, θ.

The analysis shows that the pattern of distribution of stresses at the sides and at the base is nearly same for all the cases this may be seen from the stress distribution diagrams given in Figure 4.

It is interesting to note that for a given value of $\frac{d}{b}$ with increasing tilt the moment shared by sides decreases and that by base goes on increasing. This variation may be seen from Table III.

TABLE II

$\frac{d}{b}$	Lateral load (kg)	Tilt θ	Position of point of rotation above base	Total load perpendicular to base Σv (kg)	Total load parallel to base ΣH (kg)
	241	0° 2′	0·38D	1298	241
1.75	541	0° 11′	0·40D	1298	541
	741	0° 24′	0·40D	1298	541

Total moment about '0' ΣM (kg cm)	ΣM balanced (kg cm)	Moment shared by sides *Ms*	Moment shared by base M_B	Position of point to which *Kh* belongs	*Kh*
1306240	1306200 (98%)	800653 (97%)	505567 (3%)		2·21
2930056	2930050 (99%)	2754253 (94%)	175803 (6%)	0·64D	1·70
4011699	4011690 (99%)	3690764 (92%)	320935 (8%)		1·02

Position of point to which *Kh* belongs	*Kh*
0·81D	4·9
	5·3
	13·0

TABLE III

$\frac{d}{b}$	Qh(kg)	θ	Point of rotation above base	Σv(kg)	ΣH(kg)	ΣM about 0 (kg cm)	ΣM Balanced	Ms%	M_B%
1·5	22·7	1° 6′	0·237D	189·47	26·34	1985	1961	86	14
	31·8	1° 33′	0·296D	189·35	34·37	2933	2893	79	21
	40·8	1° 54′	0·296D	188·55	47·0	3742	3716	77	23
	66·0	2° 42′	0·296D	186·6	74·30	5356	4354	66	34
1·75	45·5	1° 12′	0·23D	189	48·97	3606	3571	95	5
	100	1° 42′	0·254D	186·95	105·4	7703	7695	90	10
	127	2° 6′	0·28D	185·22	132·68	10948	10864	92	8
	136	2° 48′	0·28D	183·30	143·9	11823	11787	88	12
2·0	50	1° 32′	0·22D	188·62	54·53	3971	3952	83·5	16 5
	100	1° 50′	0·25D	186·70	106·03	7642	7568	90·8	9·2
	150	2° 0′	0·27D	186·65	155·16	11074	11065	90	10
	186	2° 54′	0·44D	180·4	193·70	12261	12214	87	13
2·5	81·8	1° 0′	0·18D	188·5	84·3	6163	6106	95	5
	118·0	1° 54′	0·25D	186·0	123·12	8533	8510	90	10
	154·0	2° 12′	0·25D	184·0	159·75	11108	10092	82	18
	190·0	2° 48′	0·27D	180·59	197·39	13556	13420	88·7	11·3

In Figure 5 moment shared by base and the sides for various values of tilt for various $\frac{d}{b}$ ratios have been plotted. As $\frac{d}{b}$ ratio increases for a given tilt moment shared by the base decreases. It may be noted that near the point of failure the moments shared by the base decreases. It may be noted that near the point of failure the moments shared by the base is about 12 percent for the majority of cases.

In case of large scale test the modes of variations are more or less similar to those observed in case of small scale test. *Kh* and *Kv* values calculated are of the order of 2 to 14. This may be attributed to the length effects.

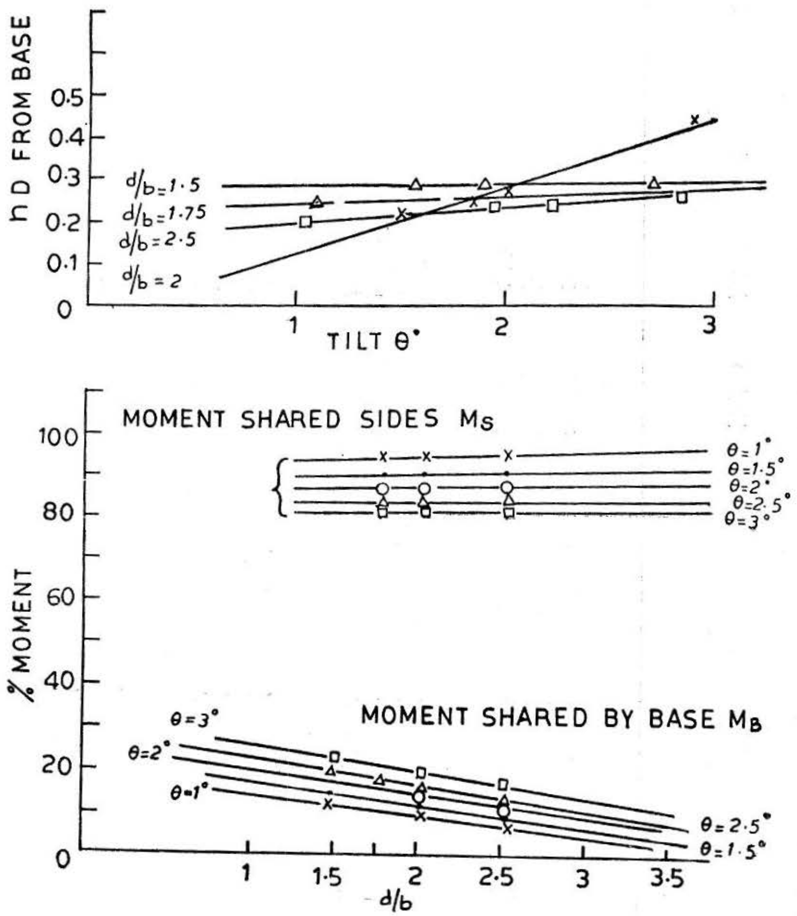


FIGURE 5 : Graphs showing relationship between d/b, Ms MB and θ.

Summary and Conclusions

It is realised that with the help of actual measurement of pressures it was possible to arrive at the balance of all the three conditions of static equilibrium within ± 5 percent of error.

It is also observed that the mode of distribution of stresses for all the conditions come out to be similar in pattern except in magnitude.

The moment shared by base goes on increasing with the tilt for a given $\frac{d}{b}$ ratio. This variation seems to be linear in nature. As the $\frac{d}{b}$ ratio increases for a given value of tilt the moment shared by base decreases. The moment taken by the base at the point of failure is of the order of 12 percent approximately for $\frac{d}{b}$ values of more than 1·5 and is 3·4 percent for $\frac{d}{b} = 1{\cdot}5$. Large scale model test results also agree with the observations made in case of small scale test.

Acknowledgement

The authors wish to express their deep sense of gratitude to the Director, I.I.T., Bombay for his keen interest. Thanks are also due to Dr. B.S. Khadilkar for his valuable guidance and Shri D.G. Divshikar and Shri C.P. Chawan and other Soil Engineering staff for the help rendered.

References

MENARD, L. (1962). Comportement D'une Foundation Profounde Soumise A Des Efforts De Renuersement, *Soils Soils*. December 1962.

MURTHY, V.N.S. Lateral Stability Analysis of Caisson Foundation, *Hungarian Academy of Sciences*.

PENDER, E.B. (1947). The Lateral Support afforded to Piers Founded in Sand, *Journal of Institute of Engineers*, Australia, July 1947.

SANKARAN and MUTHUKRISHNIAH (1969). Well Subjected to Horizontal Forces, a Model Study, *I.R.C.*, March 1969, Paper No. 273.

TERZAGHI, KARL (1943). *Theoretical Soil Mechanics*, John Wiley and Sons.