Design of In-situ Load Bearing Capacity Mechanism

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Abstract:
Major causes of structural failure are associated with bearing capacity and settlement of foundation soil. These bearing capacity and settlement are determined in laboratory and on field. The parameter obtained from the tests will either lead to under design or over design of the intended structure. The design of In-situ Load Bearing Capacity Mechanism was chosen follow by the design analysis and calculations, material selection and development of CAD model. The concept was conceived to allow for incremental loadings for each loading on the in-situ load bearing capacity mechanism for 24 hours so that the settlement will be insignificant before another loading is applied. The process will continue for the period of seven (7) days so as to allow for gradual dissipation of pore water from clay soil. The results from this test will provides civil engineers the real problem of soil on site which will help in design for the bearing capacity and settlement of foundation.

Key words:

1. INTRODUCTION

The common and traditional method of testing for bearing capacity of shallow foundations rely mainly on the collection of in-situ soil sample transfer of the sample to the laboratory and carrying out requisite tests to determine the shear strength parameters of soil. The parameters (Cohesion, C and angle of internal friction, φ) are then used to calculate bearing capacity through the use of terzaghi's equation. A lot of errors have been observed from sample collection through laboratory tests to the terzaghi's equation used for the calculation. Therefore, the bearing capacity obtained from this method is grossly inaccurate.

Attempts have been made at field and laboratory medium scale level (Dasaka 2012, Dasaka et. al 2013, Warmate, T., 2014, Warmate and Nwankwola 2014, Barnard and Heymann 2015, Shirvani and Shooshpasha 2015, Gul and Ceylanoglu 2016, Araujo *et al*. 2017, Sultana and Dey 2018 and Barnard 2019) to develop and applied In-situ and laboratory plate load test to determine the bearing capacity of soil deposits. Most of these plate load tests uses heavy but special automobile jack mounted with pressure gauges and deformation dial gauges. These mechanisms usually require a rigid supporting medium (Anchored grillage or heavy lorry truck) to prevent upward movement of the jack and hence records the deformation due to specified applied load. This test is usually rapid and the mechanism does not allow for long time duration of loading which does not aid dissipation of pore water in saturated clay deposits during testing. This can also result in to errors when used to obtain bearing capacity in clay soils

It is on these that the concept of designing a load bearing capacity mechanism that is field operated (in-situ test) was conceive. The load bearing mechanism will be loaded incrementally through a lever arm for 24 hours before the next loading and reading taken at time interval, that will allowed for gradual dissipation of pore water from the soil on site as against the use of hydraulic jack and anchored grillage or heavy loaded truck in determine bearing capacity and settlement of soil on field.

2.0 MATERIAL AND METHODS

2.1 Materials Used

The materials used for the design and their specification are listed in Table 1.

Table 1: Materials Used and Their Specifications

S/No	Components	Specification	Function and Reason
1	Lever Arm	1 meter length and tapered	Transfer load through fulcrum to the column
2	Dead loads	5kg, 10kg, 15kg, 20kg and 25kg and 50 kg	Used in loading the lever arm
3.	Frame	Made of I-section, D= B= t	Used to carry the lever arm and loads
4.	Loading Arm	Length and circular in shape	For loading the mechanism
5.	Loading Plate	Circular and 300 mm in diameter	Transfer load to the foundation soil.

2.2 Equipment

2.2.1 Linear Variable Differential Transformer (LVDT)

Linear variable differential transformer LVDT is a device that was used to observe the settlement of the plate during testing period. It enable recording of displacement continuously with the help of LVDTs at time interval. As shown in figure 1.

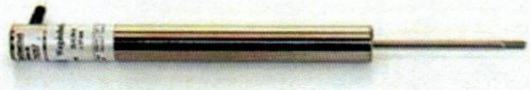

Figure 1. Linear Variable Differential Transformer (LVDT)

2.2.2 Tensiometer

Tensiometer was used to monitor Matric suction during the loading tests. Four (4) tensiometers was installed at the bottom of the pit besides the loading plate at depths of 100, 300, 600, and 800 mm. The tensiometers were installed in predrilled holes with a slightly smaller diameter than the tube diameter (20 mm). In order to facilitate a full contact of the porous element with the soil, the tensiometers were driven into the soil for a few centimeters. The tensiometers were equipped with a porous ceramic cup of 10^{-3}-m/s hydraulic conductivity and a Bourdon type vacuum gage, which was used for negative pore water pressure measurements. Readings were taken prior to and after each plate load test. As shown in figure 2

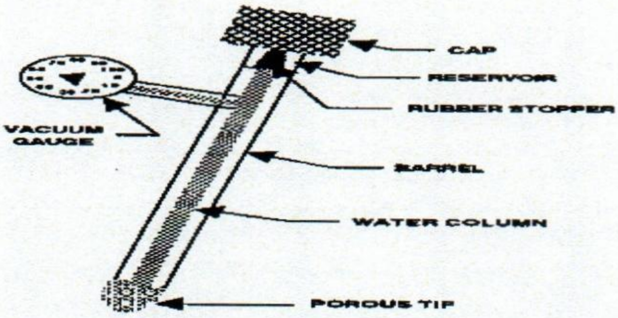

Figure 2. Tensiometer

2.3 Method

This section presented the method used for the design of the load bearing probe. Design consideration was made on the chosen concept follow by the design analysis and calculations, material selection and development of CAD model.

2.3.1 Description of Load Bearing Probe

The in-situ load bearing mechanism shown in figure 3. is a field in-situ test device that was used to determine the bearing capacity and settlement of foundation on site so as to improve on the existing/conventional plate load test and traditional laboratory test method as shown in Figure 3.

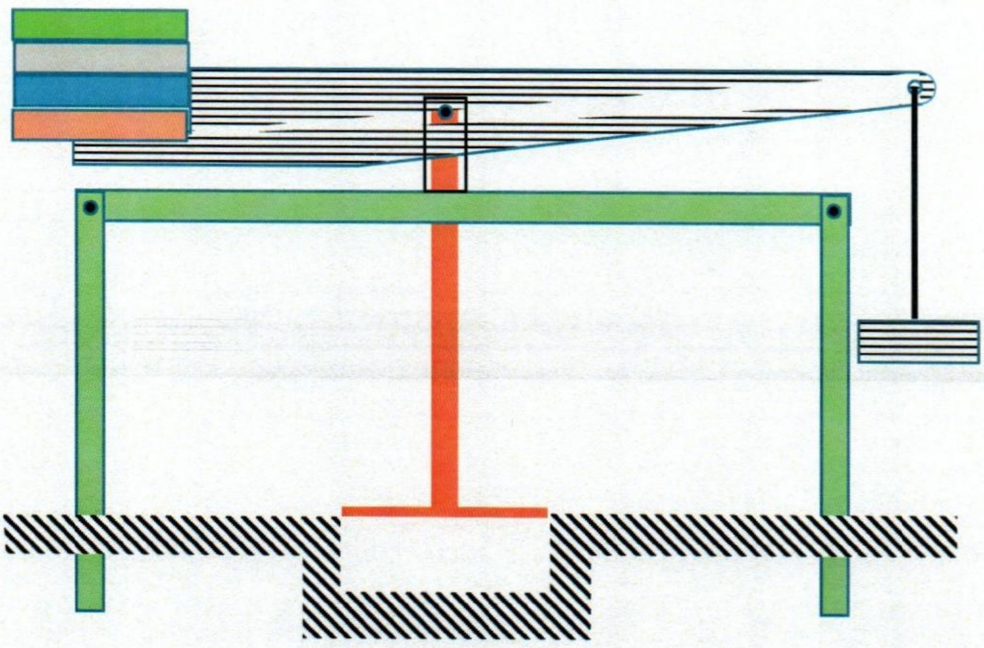

Figure 3. Sketch of Load Bearing Probe

The load bearing capacity mechanism is a straight lever with a parallel forces acting in the same plane as shown in figure 3.

The device was loaded incremental through the load hanger known as effort, P attached to lever arm and balance load W, at the opposite end to produce equilibrium of the weight on a fulcrum which was then transmit to the square base plate at the foundation level with the base plate of 300mm diameter and 25mm thickness. The load applied at the lever arm through load hanger was in order of 10kg, 10kg, 20kg, 40kg, 80kg, 160kg and 320kg. Each load placed on the lever arm was maintained for the period of 24 hours before the next incremental loadings.

2.3.2 Design of Lever Arm

A first class type of lever mechanism (Figure 4) were used in the load bearing probe because the fulcrum is located in between the load and the effort. An I-section were used for the lever arm so as to minimize the twisting due to the over hand loads. The dimensions of the lever arm are determined in the following analysis and results are presented in table 2.

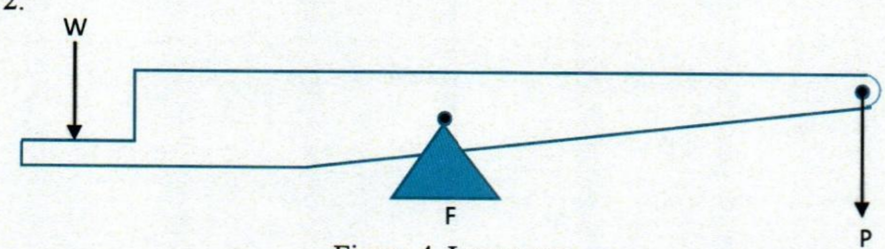

Figure 4. Lever arm

The lever that has a fulcrum F, in between the load and effort is termed first type of lever. In this case effort arm is greater than the load arm. The mechanical advantage, M.A obtained in this case should be more than one.

$$W \, x \, X_1 = P \, x \, L \qquad (1) \qquad \text{(Khurmi and Gupta 2005)}$$

Where,

P = Loads (N),

W = balancing load (N),

X_2 distance from P to the fulcrum R_1 (mm),

X_1 = Distance from Balancing load W to fulcrum (mm).

R_2 = reaction from balancing weight taken as fixed end.

P = 500,000 kg =5,000 N, L = 1,000 mm, X_1 = 350 mm, X_2 = 650 mm, W = ?

To calculate for weight of lever arm,

The total volume of the lever arm was calculated as,

V_T = 1,745,507.19 mm^3 = 0.00174550719 m^3.

The mass, M of the lever arm is:

$$M = \rho \, x \, V_T \qquad (2)$$

Where, M is mass of the lever arm,

.ρ is density of mild steel

V_T is total volume of lever arm.

7850 x 0.00174550719= 13.7 kg.

If the fulcrum is placed at x_1 = 650 mm and weight along x_1 is 2.28kg. x_2 = 350 mm and weight at end 1.67 kg. Provide additional load of 2.584 kg at the end of x_1.

From equation 1,

For equilibrium of the lever arm, $PxX_2 = W \, x \, X_1 = 4.234 \times 350 = 2.28 \times 650 = 0$

And therefore, the moment, M is =P x L= 5,000 x 1000 = 5,000,000 N/mm.

According to Khurmi and Gupta (2005). The sectional modulus of the I-section in figure 5, was computed using equation 3 and 4.

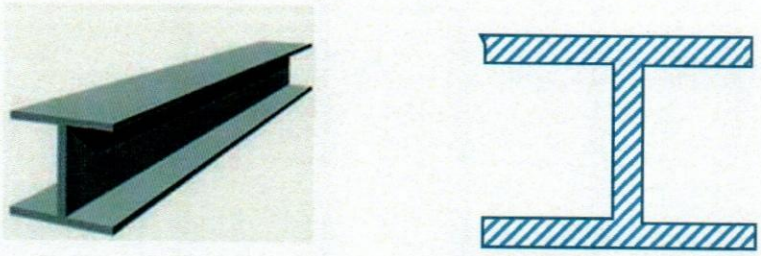

Figure 5. Proportion of I- section

Width B = 2.5t, depth D = 6t and thickness t.

Therefore,

Sectional modulus, Z

$$Z = \frac{\frac{1}{12}[2.5t(6t)^3 - 1.5t(4t)^3]}{\frac{6t}{2}} \quad (3)\ (Kurmi\ and\ Gupta\ 2005)$$

$$= \frac{37t^3}{3t} = \mathbf{12.3t^3}$$

Yield stress of mild steel is 220Mpa in table 2.5 (Kurmi and Gupta 2005)

The bending stress σ_b

$$\sigma_b = \frac{m}{z} \quad (4)\ (Khurmi\ and\ Gupta\ 2005)$$

Where,

M= moment in N mm, Z= sectional modulus of the material in mm^3.

$$220 = \frac{m}{Z} = 220 = \frac{5{,}000{,}000}{12.3t^3} = t = \mathbf{15\ mm}$$

Therefore, from Lingaiah (2004), the I-section ISMB 125 was chosen from the table (24.31). the values of I-section is tabulated in table 2.

Table 2. Showing Dimension of I-section

Sections	Value (units)
Depth of I-section D	125 mm
Breath B	75 mm
Thickness of web t_w	4.4 mm
Thickness of flanges t_f	7.6 mm
Area of section A	1660 mm^2
Sectional Modulus Z_{xx}	71800 cm^3

Therefore, the bending stress, σ, for the I-section was computed from equation 4;

$$\sigma = \frac{m}{z} \quad (4)$$

$$= \frac{5{,}000{,}000}{71800} = \mathbf{70}\frac{N}{mm^2}$$

According to (Khurmi and Gupta 2005) the allowable bending stress, $/\sigma_b/$ is given by equation 4;

$$\sigma_b = \frac{\sigma}{FS} \quad (5)$$

$= \frac{70}{4} = \mathbf{17.5N/mm^2}$

And the mechanical advantage, M. A of the lever arm is given in equation 6;

M. A $= \frac{W}{P}$ $\quad$ $eq.6.(Khurmi\ and\ Gupta\ 2005)$

$M.A = \frac{W}{P} = \frac{L_1}{L_1} = \frac{650}{350} = \mathbf{1.9\ ok}$ (According to Khurmi and Gupta 2005, mechanical advantage M. A must be less than 2. So the 1.9 is ok.)

2.3.4. Design for Pin at Fulcrum

The fulcrum pin connect the lever arm and the load transfer column via a revolute joint. Therefore, the pin is subjected to shearing stress as shown in Figure 6. And the pin load is given by equation 7. While equations 8, 9 and 10are for length of pin, maximum bending moment and sectional modulus of the materials respectively

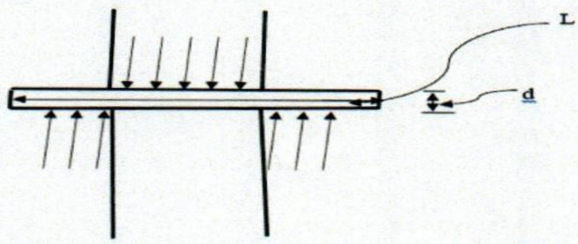

Figure 6. Pin at the fulcrum

$$P = d_1\ x\ l_1 x\ p_b \quad (7)\ (Khurmi\ and\ Gupta\ 2005)$$

Where, d_1 =diameter of pin at fulcrum and l_1 = length of the pin at fulcrum. P =dead load applied at load hanger and p_b = shear stress of the material.

If the pin is going to fail due to bearing of the pin of the fulcrum, then the pin diameter is determine as follows:

$5{,}000 = d_1\ x\ l_1 x\ p_b = d_1 1.25\ d_1 x\ 17.5 = 21.875\ d^2 =\ d_1 = \sqrt{228.57} = \mathbf{15\ mm}$

$$l_1 = 1.25\ d_1 = 1.25x17 = \mathbf{20\ mm}$$

$$l = 1.25\ d \quad (8)\ (Khurmi\ and\ Gupta\ 2005)$$

$1.25\ x\ 15 = 20\ \mathbf{mm}$

$$5{,}000 = 2\,x \frac{\pi}{2} x\ d^2\ x\ \tau = 2\ x\ \pi\ x \left(\frac{15}{2}\right)^2 x\ \tau = \tau = \mathbf{14\ N - mm^2}$$

Since the end is forked and therefore thickness of each eye

$$t_1 = \frac{l_1}{2} = \frac{20}{2} = \mathbf{10\ mm}$$

Inner diameter of each eye,

$$d_1 + 2x3 = 15 + 6 = \mathbf{21\ mm}$$

$$D = 2d_1 = 2\ x\ 15 = \mathbf{30\ mm}$$

Maximum bending moment at Y-Y

$$m = \frac{w}{2}\left(\frac{l_1}{2} + \frac{l_1}{3}\right) - \frac{w}{2} x \frac{l_1}{4} = \frac{5}{24}\ w\ x\ l_1 \quad (9)\ (Khurmi\ and\ Gupta\ 2005)$$

Where,

$\frac{5}{24} 5{,}000\ x\ 20 = \mathbf{20{,}833.33\ Nmm}$

Sectional modulus, as given in equation 10

$$Z = \frac{\pi}{32}(d_1)^3 \quad (10)\ (Khurmi\ and\ Gupta\ 2005)$$

$\frac{\pi}{32} x 15^3 = \mathbf{331.34\ mm^3}$

Bending stress induced,

$$\sigma_b = \frac{m}{z} = \frac{20{,}833.33}{331.34} = \mathbf{63\ MPa}$$

2.3.5 Design of the frame.

The frame is an assembly where the lever arm and the load is placed, the frame consist of I-beam and I-section column. The load are transferred to the crossing beam and in turn transfer to the column as shown in figure 3.

a. Design of Crossing Beam that Support Lever Arm

The cross beam is used to support the load from lever arm and transfer to the column. It is design using equation 11 and is shown in figure 7. The proportion of the support beam is taken as t =thickness, h = depth as 5t. the result is shown in table 3.

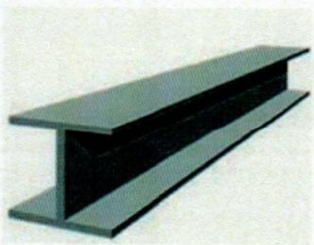

Figure 7. Crossing Beam

Moment of inertial I,

$$I = \frac{1}{12}[BxD^3 - bxd^3] \qquad (11)(Khurmi\ and\ Gupta\ 2005$$

$$I_{xx} = \frac{1}{12}[4t\,(5t)^3 - 3t(3t)^3] = \frac{\mathbf{419}}{\mathbf{12}}\boldsymbol{t^4\,mm^4}$$

Sectional Modulus Z,

$$Z = \frac{I_{xx}}{\frac{5t}{2}} = \frac{419t^4}{12}x\frac{2}{5t} = \frac{419}{30}t^3 = \mathbf{13.97t^3}$$

(From table 2.5 Khurmi and Gupta 2005) yield stress of 220 Mpa

However, bending stress σ_b,

$$\sigma_b = \frac{m}{Z} = 220 = \frac{5{,}000{,}000}{13.97t^3} = t = \sqrt[3]{1{,}626.86} = \mathbf{12\ mm}$$

$$Z = 13.97x\ 12^3 = 24{,}140.61\ mm^3$$

(From table 24.41 Lingaiah 2004) I-section chosen for the crossing beam is ISLB 75. As shown in table 3

Table 3. Showing Dimension of section

Sections	Value (units)
Depth of I-section	75 mm
Breath	50 mm
Thickness of web t_w	3.7 mm
Thickness of flanges t_f	5.0 mm
Area of section A	7.71 cm^2
Sectional Modulus Z_{xx}	19.4 cm^3

b. Load Transfer Column

The load transfer column is attached with the fulcrum that transfer the dead load to base of the foundation. The proportioning of load transfer column is shown in figure 8. Using Rankine's method to design for the cripple load as shown in equation 12, 13 and 14. Shear stress at equation 15 and the results is shown in table 4.

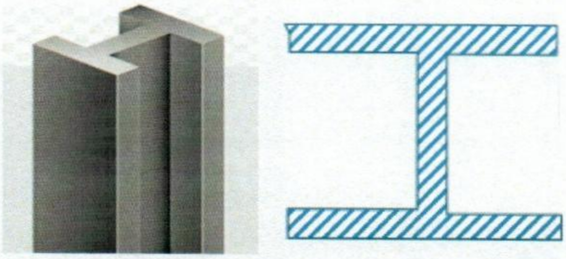

Figure 8. I-section column.

Area of the section, A =LxB (12) (*Khurmi and Gupta* 2005)

A = 2(4txt) + 3t x t =11t^3

Moment of inertial in X-axis, I_{xx}

$$I_{xx} = \frac{1}{12}[4t\,(5t)^3 - 3t(3t)^3] = \mathbf{\frac{419}{12}t^4\,mm^4}$$

Moment of inertia in Y-axis, I_{yy}.

$$I_{yy} = \left[2x\frac{1}{12}tx(4t)^3 + \frac{1}{12}3txt^3\right] = \mathbf{\frac{131}{12}t^4\,mm^4}$$

Therefore,

$$\frac{I_{xx}}{I_{yy}} = \frac{419}{131}x\frac{12}{131} = \mathbf{3.2}$$

Since the value of ${I_{xx}}/{I_{yy}}$ lies between 3 and 3.5. The I-section is quite satisfactory (kurmi and Gupta 2005).

Also, (table 4.3 of Kurma and Gupta 2005) factor of safety was taken as 4 for cripple load on column.

$W_{cr} = \frac{\sigma_c A}{1+a\left(\frac{L}{2K_{xx}}\right)}$ (13) (*Kurmi and Gupta* 2005)

Where,

W_{cr} = cripple load

.σ_c = compressive yield stress

A = cross sectional area of the column

.a = Rankine's constant

K = least radius of gyration

L = equivalent length of column

However, since the column is fixed, effective length is L = L/2 =2,000mm/2 = **1,000 mm**

.σ_c = 320 MPa = 320 N/mm^2 and a = 1/7,500.

$$w_{cr} = w\,x\,factor\ of\ safety = 5{,}000x4 = \mathbf{20{,}000N}$$

Consider list moment of inertia,

$$I_{xx} = \frac{1}{12}[4t\ (5t)^3 - 3t(3t)^3] = \frac{\mathbf{419}}{\mathbf{12}}\boldsymbol{t^4\ mm^4}$$

And radius of gyration k_{xx} of the least moment of inertia, as given in equation 14

$$K_{xx} = \sqrt{\frac{I_{xx}}{A}} \qquad (14)\ (\textit{Kurmi and Gupta}\ 2005)$$

$$k_{xx} = \sqrt{\frac{I_{xx}}{A}} = \sqrt{\frac{419t^4}{12} x \frac{1}{11t^2}} = \mathbf{1.78t}$$

Equivalent length of column for both ends fixed.

$$L = \frac{L}{2} = l = \mathbf{1,000\ mm}$$

From eq.13. Rankine's cripple load, W_{cr},

$$w_{cr} = \frac{\sigma_c x A}{1 + a\left(\frac{L/2}{k_{xx}}\right)^2}$$

$$20,000 = \frac{320x11t^2}{1 + \frac{1}{7,500} x \left(\frac{1000}{1.78t}\right)^2}$$

Thickness, t = **4.3 mm**

However, (Table 24.31 Lingaiah 2004). I-section chosen for the column is ISLB 75. As shown in table 4.

Table 4. Showing Dimension of section

Sections	Value (units)
Depth of I-section	75 mm
Breath	50 mm
Thickness of web t_w	3.7 mm
Thickness of flanges t_f	5.0 mm
Area of section A	7.71 cm^2
Sectional Modulus Z_{xx}	19.4 cm^3

Shear Stress τ,

$$\tau = \frac{F}{A} \qquad (15)\ (\textit{Kurmi and Gupta}\ 2005)$$

$$\tau = \frac{5,000}{771} = \mathbf{7\ N/mm^2}$$

c. Design of anchor Leg

The anchor column legs is made up an I-section mild steel with the crushing stress of $\sigma_c = 320\ Mpa$ with Rainkine constant, $a = {}^{1}/_{7500}$

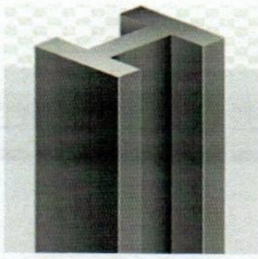

Figure 8. Anchor column legs

Radius of gyration for an I-section, K, from eq. 14 and results at table 5

$K = \sqrt{\frac{I_{xx}}{A}}$

Moment of inertia about x-axias

$$I_{xx} = \frac{1}{12}[4t\ (5t)^3 - 3t(3t)^3] = \frac{\mathbf{419}}{\mathbf{12}}\boldsymbol{t^4\ mm^4}$$

The factor of safety is taken as 4

$$k_{xx} = \sqrt{\frac{I_{xx}}{A}} = \sqrt{\frac{419t^4}{12}x\frac{1}{11t^2}} = 1.78t$$

From eq. 13

$$w_{cr} = \frac{\sigma_c xA}{1 + a\left(\frac{L/2}{k_{xx}}\right)^2} = 20{,}000 = \frac{320x11t^2}{1 + \frac{1}{7{,}500}x\left(\frac{2000}{1.78t}\right)^2}$$

Thickness, t = 8 mm

(From table 24.41 Lingaiah 2004) I-section chosen for the anchor leg ISLB75 is shown on table 5

Table 5. Showing Dimension of section

Sections	Value
Depth of I-section	75 mm
Breath	50 mm
Thickness of web t_w	3.7 mm
Thickness of flanges t_f	5.0 mm
Area of section A	7.71 cm^2
Sectional Modulus Z_{xx}	19.4 cm^3

Shear stress τ,

$$\tau = \frac{F}{A} = \frac{5,000}{771} = \frac{5,000}{771} = 6\ \boldsymbol{N/mm^2}$$

2.3.6. Design of Loading Arm

Loading arm is circular mild steel rod attached to the lever arm through a pin and was used in loading the load bearing probe. Using equation 7

P = area of rod x $shear\ stress.\sigma_t$

$5,000 = \frac{\pi}{4} d^2 x 220,\ d = \boldsymbol{6mm}$

Safe tensile load = stress area x σ_t

Shear area A $= \frac{\pi}{4} x 6^2 = 28.27\ mm^2$

Safe tensile load = 28.27 x 220 = **6,219N**

Design of Loading Arm Pin.

From equation 7.

$P = d_1\ x\ l_1 x\ p_b$

Let, d_1 =diameter of pin at loading arm

And l_1 = length of the pin at loading arm

Let consider bearing of the pin at loading arm

5,000 = $d_1\ x\ l_1 x\ p_b = d_1 1.25\ d_1 x\ 17.5 = 21.875 d_1^2 = d_1 = \boldsymbol{15\ mm}$

$$l_1 = 1.25\ d_1 = 1.25 x 15 = \boldsymbol{18.75\ mm}$$

Check for shear stress, from equation 15.

$P = 2x\frac{\pi}{4} x\ d^2 \tau$

$$5,000 = 2x\frac{\pi}{4} x\ 15^2 \tau$$

$\tau = \boldsymbol{14.15\ MPa\ is\ ok}$ (According to Khurmi and Gupta 2005)

Since the end is forked and therefore thickness of each eye

$$t_1 = \frac{l_1}{2} = \frac{18.75}{2} = \mathbf{9.375\ mm}$$

Inner diameter of each eye,

$$d_1 + 2x3 = 15 + 6 = \mathbf{21\ mm}$$

$$D = 2d_1 = 2\,x\,15 = \mathbf{30\ \ mm}$$

Maximum bending moment at Y-Y

$m = \frac{w}{2}\left(\frac{l_1}{2} + \frac{l_1}{3}\right) - \frac{w}{2}x\frac{l_1}{4} = \frac{5}{24}\ w\,x\,l_1$

Where,

$\frac{5}{24}5{,}000\ x\ 18.75 = \mathbf{19{,}531.25\ Nmm}$

Sectional modulus,

$Z = \frac{\pi}{32}(d_1)^3$

$\frac{\pi}{32}x15^3 = \mathbf{331.34\ mm^3}$

Bending stress induced, A

$$\sigma_b = \frac{m}{z} = \frac{19{,}531.25}{331.34} = \mathbf{5.83\ MPa}$$

3. Results and Discussion of the Results

3.1 Results of Lever Arm Design Analysis

The result of the design analysis are presented in tables 6 – 8. Table 6, shows the design results of the lever arm. The minimum safe dimensions of the lever arm presented for the I-section used.

Table 6: Lever Arm Results

Sections	Value (units)
Depth of I-section D	125 mm
Breath B	75 mm
Thickness of web t_w	4.4 mm
Thickness of flanges t_f	7.6 mm
Area of section A	1660 m^2
Sectional Modulus Z_{xx}	71800 cm^3

The anchor legs provide support for the entire frame of the load bearing capacity probe. The design results are presented in Table 7. The results shows that maximum shear stress during working is far less that the yield stress of the mild steel.

Table 7: Results Leg Anchor

Sections	Value
Depth of I-section	75 mm
Breath	50 mm
Thickness of web t_w	3.7 mm
Thickness of flanges t_f	5.0 mm
Area of section A	771 mm^2
Sectional Modulus Z_{xx}	19400 mm^3

Table 8: Other results includes.

Sections	Value
Area of load bearing arm	28.27 mm^2
Length of the load bearing arm	600 mm
Diameter of the pin	6 mm
Length of the pin	18.75 mm

4. Conclusion

The design analysis of in-situ load bearing capacity mechanism was successfully conducted, which will facilitate the fabrication and final performance evaluation of the mechanism. The similar mechanism presently in use are laboratory and field models for sand soils only. They don't facilitate testing at the site of the project for long period of time. Therefore, this design is mainly for site experimentation for long time as against the previous tests. A CAD model of the design concept was developed, followed by design analysis and synthesis of the required dimensions of the components of the load bearing capacity mechanism. The minimum thickness and load area of the lever arm and anchor legs are 4.4mm, 3.7mm and 16.60 mm^2, 7.71mm^2 respectively.

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