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A Geotechnical and Structural Analysis and Design of Transformer Foundation Using Finite Element

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ABSTRACT

The requested soil pressure is to develop a structural system to support all proposed loads in consistency with the architectural design, The analysis was performed using a finite Element technique. Shell elements have been constructed for the mathematical model and relevant vertical loads are applied to the shell elements. The proposed project to process the analysis and design the transformers foundations was located in southern Iraq. 6.5×9 m concrete foundation was intended to transfer loads from the transformers to the under beneath soil including wind and seismic loads. Models are created using CSI-SAP program was selected to simulate the mat foundation. The analytical equations were depended to validate the obtained results from finite element model. A real allowable soil pressure and stiffness modulus of soil in the field was considered to relevant needed parameters to simulate the soil mass in numerical model. The obtained results from the finite element showed generally coincidence with mathematical equations to calculate the reinforcement's areas, shear and moment values. The analysis of finite element from software program gave approved results of the estimated settlement under the foundation compared with the analytical equations.

1. INTRODUCTION

In spite of the foundations are used to support the buildings and many civil projects but it used also in various equipment as supports for example breakers, switchgear and power transformers. Using the foundation under electrical equipment needs high caution where there is occasion of frost heave or attacking to some liquids. This may lead to dangers with equipment that have rigid bus connections and, in some times, result in an operational malfunction of this equipment. Due to the connection of electrical cables scientific research suggests that settlement or differential settlement has been a major cause of failure in performance of transformer and may be cause damage in it. Therefore, the good estimation of applied loads forms valuable step in design of foundations of transformer .

Many researchers used finite element models to simulate the foundations under different loads for predicting some values as settlements and bearing capacities of soils [1-4]. Analysis the shallow foundation at different depth under vertical, inclined, eccentric, loads using finite element method (FEM) software gave a good agreement when compared with previous studies [5]. Estimation of settlement and bearing capacity of strip footing using software program was conducted by Khalil et al. [6] and compared with experimental works and the results gave same behavior.

For over twenty years, many researchers have been working at field of the finite elements' application to the analysis of practical engineering problems.

Tank et al. [7] simulated the machine foundation system and analyzed dynamic response of foundation in SAP 2000 software. The results of displacement values are validated by previous study.

Liu [8] prepared foundation as a case study for a steam turbine generator and the procedures of analysis and design are described in detail. Modal of FE analysis using SAP software was used to analyze seismic response spectrum in time history. He found that FEM help design engineers to recognize the various advantages to find the best modeling option for any given case.

Using finite element program provide ability of estimate the settlement at any time under various loads including wind and seismic loads. Special requests should be provided when design the foundation under the transformer as bearing walls, pits and beams to carry iron rails which are considered principals of manufacturer of the transformer for proper operation. Knowing these data help the designers to select the preferable foundation with optimal design with limited mistakes.

The present article deals with one of these cases which represents study rigid foundation of electrical transformer 132/33 kV constructed in south of Iraq. The methodology of the work provides a guide to how to use the provided data to completed design of rigid foundation carrying various loads. Problem of this study was simulated within three-dimensional finite element software to design the structural elements. The structural software needs a professional method to input geotechnical requirements such as bearing capacity of soil to finish the analysis properly.

2. METHODOLOGY

The main parameters of a typical transformer foundation design are: Identifying requirements of transformer, soil investigation, geotechnical design of foundation, calculation the loads and check settlements and finite element modelling.

Analysis and design methodology of transformer foundation contains various stages which is explained by the flowchart shown in Figure 1.

2.1 Principal requirements of transformer foundation

Many of manufactured companies attach some civil instruments to operate and maintain the transformers in good performance. One of these guides are the distance between the railway of the transformer and the dimension of the pit under transformer. Almost, the distance between the railways is 1.505m and the height of pit from the foundation to mesh of gravel is minimum 1 m. So, depending on the pervious requirement, the foundation is drawing as shown in Figure 2.

Transformer has length=5.10 m, width=4.5 m and the height=5.00 m. The total calculated weight of unique transformer (including oil)=800 kN. A fire wall is constructed to avoid spate from the two transformers and also it used to protect each transformer of other. The transformer is installed on pedestals 0.6 cm in thickness and 0.9 m height, these pedestals carry iron railway to move the transformer in one way. On the two sides of the transformers iron meshes are putted on concrete pits and covered with suitable stone. This system needs to be constructed on raft foundation to prevent the differential settlement which may be cause damage for the electrical cables. The soil beneath the foundation was enhanced by replacing the weak soil and some layers of crushed stone, sub base and concrete layer were implemented according to recommendation of soil investigation reports.

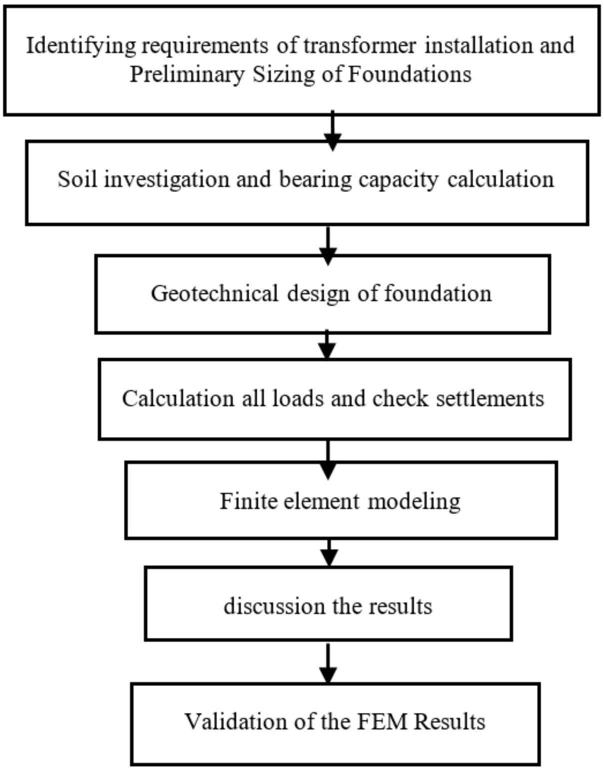

Figure 1. Schematic diagram of a transformer foundation

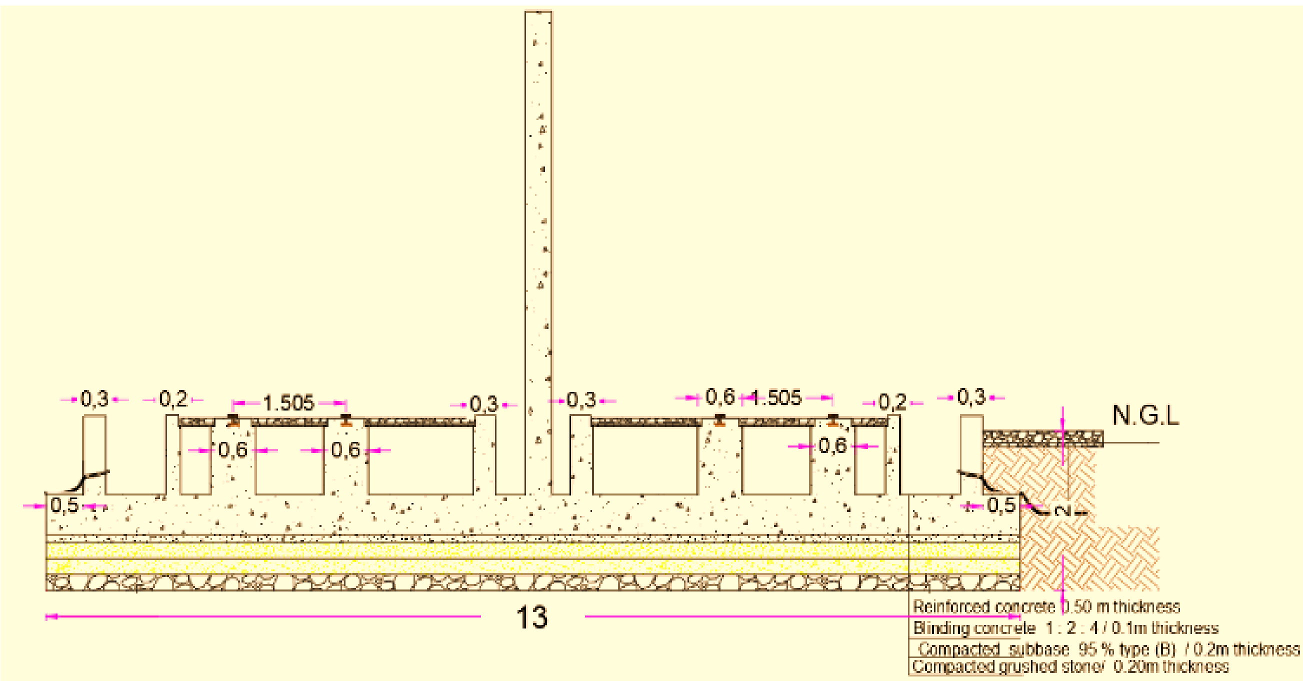

Figure 2. Principal requirement for transformer foundation

2.2 Site investigation

To recognize the soil strata a soil investigation was planned and executed. Two boreholes at a depth of 10 m each one was conducted in the field and many required tests were done. Standard penetration test, SPT, is considered one of the famous tests, so it was done during progressing of boring. This test is performed according to ASTM D 1586-99 [9].

Figure 3 shows the characteristics of subsoil profile for two bore holes and S.P.T diagrams.

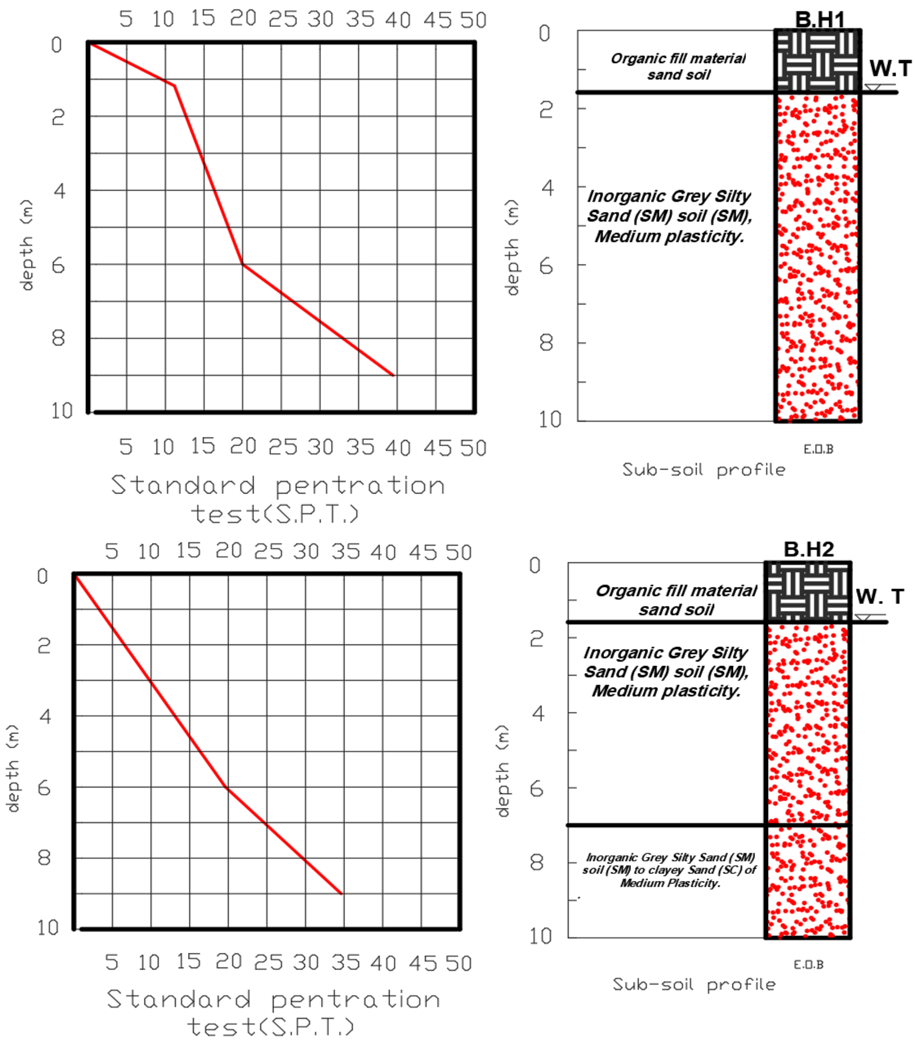

Figure 3. Soil profile and SPT numbers with depth

The profiles of two bore holes explain the following:

a) A grey organic fill material, loose sand soil, this layer extends from 0 to 1.5 meters.

b) Layer of inorganic gray silty sand soil (SM) to clayey sand (SC), of medium plasticity. Loose to medium density and this layer extended from 1.5.0 to 6.0 m.

A layer of inorganic gray SM, of medium plasticity. Medium density and this layer extended from 6.0 to 10.0 m.

Based on field investigation and results of laboratories test, the bearing capacity using static Terzaghi' formulas were estimated.

Using test data from field tests, the allowable bearing capacity and settlement of footings on coarse-grained soils are often determined on empirical methods. SPT "N" values at various depths using the dynamic method to estimate the bearing capacity for cohesion less soil in 25 mm of settlement was considered as field test [10, 11].

Accordingly, the bearing capacity of the soil under the foundation depending on SPT blows number is summarized in Table 1.

The direct shear tests were used to guess the bearing capacity using static method because most soil consisted of sand with some silts. Terzaghi equations with Meyerhof's modification were used to calculate the bearing capacity values [12].

Table 2 shows the bearing capacity values for the soil beneath foundation using shear strength parameters.

From the results Table 1 of SPT and direct shear tests, there are weak layers for all investigated depth; the failure of soil is of punching shear.

Gathering information of SPT and laboratories tests and relying on accepted engineering practices, 45 Kpa allowable capacities can be used in the design of raft foundation. From the results of SPT and direct shear tests, there are weak layers for all investigated depth; the failure of soil is of ***punching shear***. So, the designer should choose suitable footing with safety factor more than 3 and that does not exceed the allowable bearing capacities

During the soil investigation, the level of underground water was measured at end of boring which was 1.5m underground surface and the average unite weight of soil about 18 kN/m^3.

Table 1. Allowable bearing capacity according to SPT test

Depth (m)	SPT (N) Total for 300 mm BH.1	SPT (N) Total for 300 mm BH.2	Average SPT (N) for 300 mm	Average B.C (kN/m^2)
1.5	12	6	9	46.49
3.0	-	-	-	-
4.5	-	-		-
6.0	15	19	17	78.51
7.5	-	-		-
9.0	39	34	36	117.87

Table 2. The allowable bearing capacity from direct shear

BH. No.	Depth (m)	Cu (kN/m²)	ϕ	q_a (kN/m²)
B.H.1	3.0	2	14.1	49.5
B.H.2	3.0	6.2	13.94	64

2.3 Geotechnical design of footing

The electrical transformer footing is basically designed depending on conventional method. Depending on the applied loads the geometry of the foundation will be considered and the foundation will be embedded to 1.5 m depth. According to the manufacture details of transformer as the dimensions and weight, the primary dimensions of raft is 13 m as length and 5.5 m as width. The thickness of raft foundation was assumed 0.5 m to resist the punching and wide bean shear. The dimension of foundation was selected depending on two criteria; the first is the requirement of electric standard designs for transformer and the second bearing capacity of the soil under foundation. This primary dimension will be checked later to overcome the elastic and differential settlement and then is modified if it doesn't comply the bearing capacity.

2.3.1 Calculation the static loads

Length of transformer (L)=5.1 meters.

Width of transformer (B)=4.5 meters.

Height of transformer above top of Pedestal (H)=5.00 meters.

Each transformer has total weight (including oil)=800 kN.

So, the total load of the pad foundation and inverted beams with fire wall=1423 kN.

The total load of two transformers and foundation=1600 + 1238=3023 kN.

2.3.2 Calculation the wind load

The effect of the wind load will be considered in this article, so maximum wind velocity (Vb) will be taken=170.0 km/hr.

The velocity of wind was considered depend on the previous record of winds in city.

The design wind pressure (Fz) is calculated according to the following equation [13].

$$F = A \times P \times Cd. \tag{1}$$

where, F=load of wind (N).

$$P = pressure\ of\ wind = 0.00256\, V^2 \tag{2}$$

- The speed of the wind (V) is 170 km/hr=47.2 m/s.

= 0.613×(47.2)²=1365.67 N/m².

A=the area of the facade=6.80 m (height)×5.50 m (width)=37.4 m².

Cd= factor =1.2.

F_z=37.4×1365.67×1.2=61291.26 N=61.3 kN.

This equation considers the location of the transformer whether in open or closed area, so the Cd factor was taken according this criterion.

2.3.3 Soil stability check

In several cases, any foundations are generally subjected to the vertical load in addition moments, so, the pressure distribution from foundation on soil is not uniform. The pressure is distributed off on the soil as [10]:

$$q_{\max,\min} = \frac{\sum p}{BL}\left(1 \pm \frac{6e}{L}\right) \tag{3}$$

where,

P=the total applied load.

B and L represent length and width of the foundation.

E=eccentricity of the footing.

The total load of two transformer and foundation=3023 kN.

Maximum moment at the base due to maximum horizontal force=61.3 kN ×3.5=214.6 kN.m.

Eccentricity for the footing=214.6/3023=0.071 m.

Eq. (3) with related data produce two values of pressure beneath footing on soil one represents the maximum and other minimum as following:

$q_{\max}$=43.6 kN/m² which less than the allowable bearing capacity of soil.

$q_{\min}$=40.8 kN/m²

2.3.4 Settlement check

Under all loads, any soil will suffer consolidation or settlement leading damage of structures stablished on it. If this settlement is not stayed to allowable value, the favorite use of this structure may be weakened and next structure's life may be reduced. settlement of structures may be uniform or some time nonuniform which is named differential settlement [11].

The loads from any structure cause stress to the soil that happen when a structure is constructed on a foundation consisting of soil. The stability and safety of the structure depend on two most important requirements which are:

(1) The vertical deformation which is known settlement of the soil must be within permissible values;

(2) The shear strength of soil beneath foundation should be safe to resist the stresses induced [14].

Because all the soil profile illustrates that soil is sand, so the elastic settlement is considered to check the settlement under foundation.

Theoretically, if the foundation is perfectly flexible, the settlement may be expressed as [10]:

$$Sc = \Delta\sigma(\alpha B')\frac{1-\mu^2 s}{Es} IsIf \tag{4}$$

where,

Δσ=net calculated pressure on the foundation, for two transformer and footing=2814/66.3 =42.28 kN/m².

μ_s=Poisson's ratio for soil=0.3.

E_s=average modulus of elasticity for soil beneath the foundation which is measured from z=0 to z=5B=9000 kN/m².

B'=B/2 for foundation center. Where the width of footing (B) is 5.5 m, so B= 5.5/2 = 2.75 m.

Is=shape factor which depend on the length, width and depth of footing underground=0.0871.

α=factor that relates on the foundation settlement which is wanted to calculate. At the *center* of the foundation for calculation of settlement =4.

I_f=depth factor which depend on the Poisson's ratio of soil, length, width and depth of footing underground=0.83.

Accordingly, the elastic settlement from data above=3.39 mm which is within the permissible settlement.

The value of settlement is considered acceptable and less than the allowable settlement under certain structures which is 25 mm [10, 11, 15].

Table 3. Material data

Property	Concrete	Rebar
Density (kN/m^3)	24	76.97
Modulus of elasticity (kN/m^2)	25,742,960.2	200000000
Strength (kN/m^2)	30,000	400,000
Poisson's ratio	0.2	0.3

Table 4. Structural elements data

Property	Raft Foundation	Wall	Inverted Beam
Width (mm)	-	-	800
Thickness (mm)	500	200	600
Cover (mm)	75	25	75

2.4 Finite element modeling

FEM is one of the excellent-established techniques to solve of complex problems using the computer in various fields of civil engineering.

The foundation material and the concrete are modelled in finite elements as linear elastic materials with specified young's moduli and poison's ratio [16].

To perform structural analysis and design for concrete foundation, CSI-SAP 2000 software V14 was selected and some assumptions should be assumed to create the numerical model as illustrated in Tables 3 and 4.

To simulate the soil under the foundation, the spring elements are developed and distributed under the foundation after dividing it to regulator small elements. The raft was divided to 0.5×0.5 m size of elements and a spring will be attached under center of each element.

The contestant stiffness of spring is in vertical direction (Z-direction) and the required unit is in kN/m^3.

Bowles [15] has suggested the following for approximation calculation to k_s depending on the allowable bearing capacity q_a:

$$k_s=40\,(SF)\,q_a\ (\text{kN/m}^3) \tag{5}$$

where:

q_a=the allowable bearing capacity of soil furnished in kPa.

SF=safety factor which almost equal to 3.

This equation is founded on $q_a=q_{ult}/SF$ at a settlement ΔH=0.0254 m in ultimate soil pressure.

The subgrade modulus is taken calculated k_s=5400 kN/m^3.

The elasticity modulus of footing concrete was taken as following equation [17]:

$$E_c=4700\,(fc')^{1/2} \tag{6}$$

where:

fc′=the compression strength of the concrete.

The raft foundation and fire wall are a shell element with related thickness, compressive strength and the unite weight.

After inputting the data required in Tables 3 and 4 which represent properties of the structural parts, a real dimension and size were created in the SAP 2000 model. To simplify inputting the structural parts many grids were created in three dimensions and the distance between grids represents size of footing and fire wall [18].

3. RESULTS AND DISCUSSION

The site requirement is to install two neighbor transformers in one location, so the suggested footing was decided to be one raft foundation under the two transformers. In this part, to represent the foundation as a finite element mode SAP 2000 software program was used.

Figure 4 represents the analyzed model from CSI-Sap package which illustrates the raft footing and the fire wall with inverted beams.

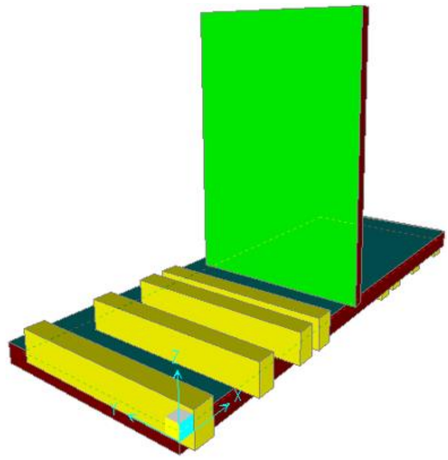

Figure 4. FEM of two transformers footing

3.1 Structural design raft foundation

Finite element software has ability to explain the moment in each direction after analysis the model according to load pattern. Figure 5 represents the moment plan in long direction shows the intensity of moment in each region as color with index of each color reflect the values of moments.

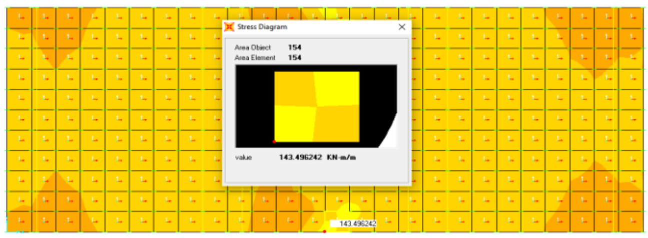

Figure 5. Moment plan in long direction

From Figure 5, the maximum moment in long direction was 143.3 kN/m^2. Therefore, to find the reinforcement using this moment analytically and the check this reinforcement ratio with that had from FEM.

The area of steel according to the provided moment can be calculated as the following equation:

$$A_s=\frac{M}{j.d.f_y} \tag{7}$$

So, A_s=1008 mm^2/m which is greater than minimum reinforcement according to ACI-code 2005 which is 0.002 bh=850 mm^2

Form FEM design characteristic the reinforcement area in bottom face in longitudinal direction was 1096 mm^2/m as shown in Figure 6. The two values of analytical and FEM result are convergent significantly.

Figure 7 represents the reinforcement plan in transverse direction. The reinforcement area in bottom face in transverse direction was 1083 mm^2/m which is greater than minimum reinforcement according to ACI-code 2005 which is 0.002 b.h=850 mm^2. For top reinforcement in long and transverse direction, Figure 6 shows the reinforcement area for one meter length. It was noted that the required flexural area of reinforcement is 960 mm^2/m.

It can be used 6 Ø 16=1206 mm^2/m is used as depended area in top faces for the foundation which is greater than the minimum reinforcement according to ACI code (0.002 b.h=850 mm^2/m).

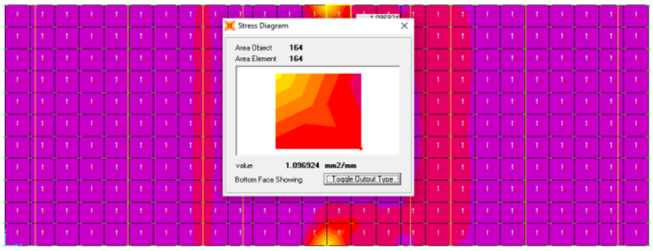

Figure 6. Shell reinforcement diagram in long direction at bottom face

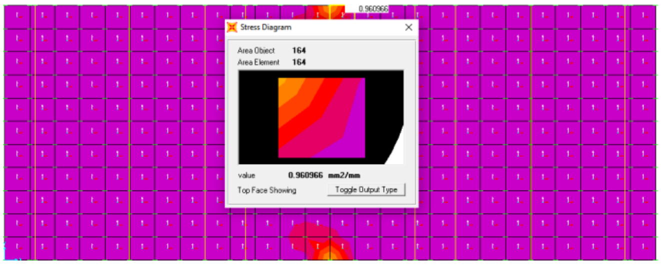

Figure 7. Shell reinforcement diagram in transverse direction at top face

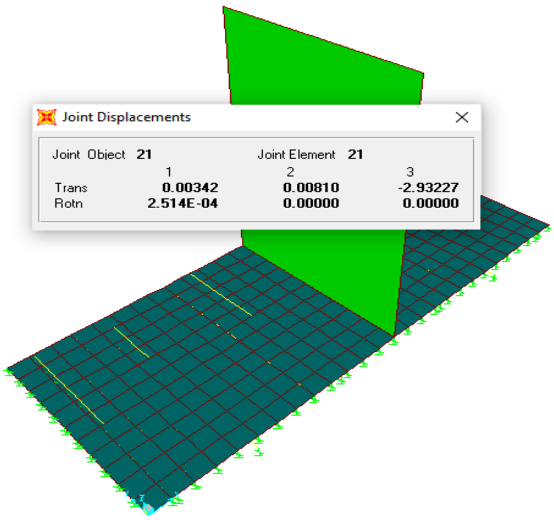

Figure 8. Shell displacements

3.2 Settlement check

To check the settlement and the actual bearing pressure on the soil from finite element analysis, the deformed shape tool explains the values of the displacements on each element on the foundation. Figure 8 illustrate the maximum displacements on middle span of the foundation which is 2.93 mm. comparing the FEM result with calculated value using Eq. (4) in paragraph 4.4 which was 3.39 mm, it is considered almost convergent because using the spring stiffness in numerical model and limited divided area for footing. The obtained results from the present finite-element models seemed that the mathematical models are suitable to predict the load–deflection behavior of reinforced concrete foundations subjected to seismic or static loads [19].

3.3 Structural design inverted beams

To design the inverted beam and calculate the required reinforcement, SAP 2000 software can show the internal maximum moment and shear on frames. Figure 9 illustrates the maximum moment and shear diagram for one beam, it was noticed that the maximum moment and shear are 472. 15 kN.m and 373.4 kN respectively.

d= effective depth of foundation= 800-30=770 mm.

A_s=1824 mm^2/m.

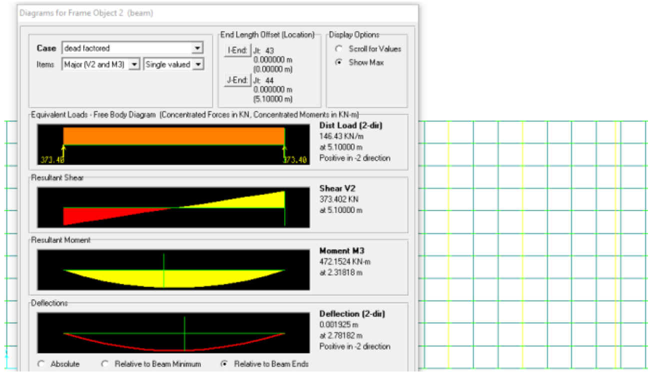

Figure 9. Beam moment and shear diagram

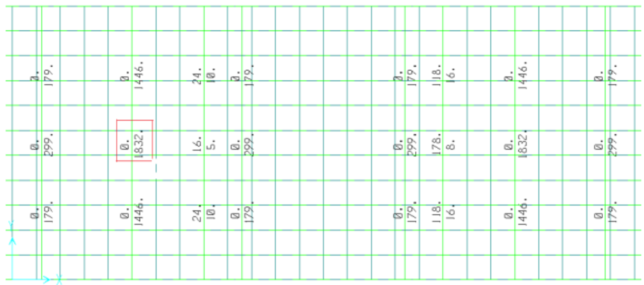

Figure 10. Reinforcement areas for beams

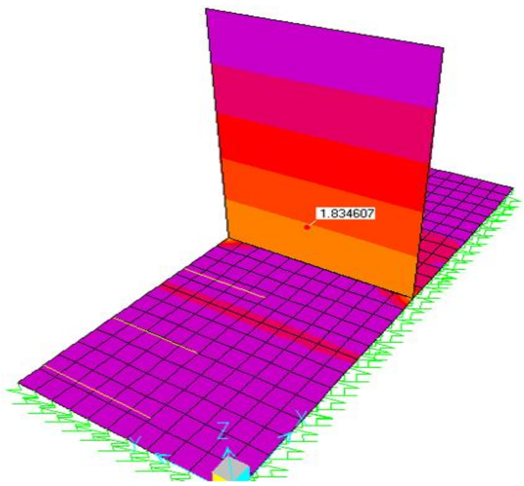

Figure 11. Reinforcement areas for fire wall

The minimum reinforcement according to ACI-code 2005 which is 0.002 b.h=960 mm^2. But because the beam is a deep beam and must be connected structurally with the raft foundation using vertical bars, the distribution of the reinforcement will be distributed on top and two sides of the beams.

The software program can give the reinforcement after conduction the design process as shown in Figure 10 which was 1832 mm^2.

The retaining side wall on each side will be reinforced as that done for the inverted beams.

The reinforcement of fire wall can be known from program design display as shown in Figure 11, where the required vertical reinforcement was 1834 mm/m. So, use 10 Ø 16=2010 mm^2/m is adequate to resist the flexural moment.

4. VALIDATION OF THE FEM RESULTS

A distinctive agreement was obtained between the FEM with the use of the developed programs software and theoretical load–deflection results [19-21].

The FE analysis seemed a reasonably good coincidence with the results of laboratory experimental; a discrepancy of within 11 to 25% when nonlinear finite element analysis was performed to study the geotechnical behavior to shell footings [16, 22, 23].

According to the obtained results, Table 5 shows the results of design of foundation and fire wall. From this table it is clear to see the closer results between the analytical and these obtained from numerical model. This convergence in the results is due to the correct input of the properties and analysis the model by FEM which depend mainly on same ACI-code requirements.

Table 5. Results of the analytic ad FEM

Property	Analytic	FEM
Longitudinal reinforcement (Footing)	1008 mm^2	1096 mm^2
Transvers reinforcement (Footing)	1083 mm^2	960 mm^2
Settlement	3.39 mm	2.93 mm
Longitudinal reinforcement (Beam)	1824 mm^2	1832 mm^2

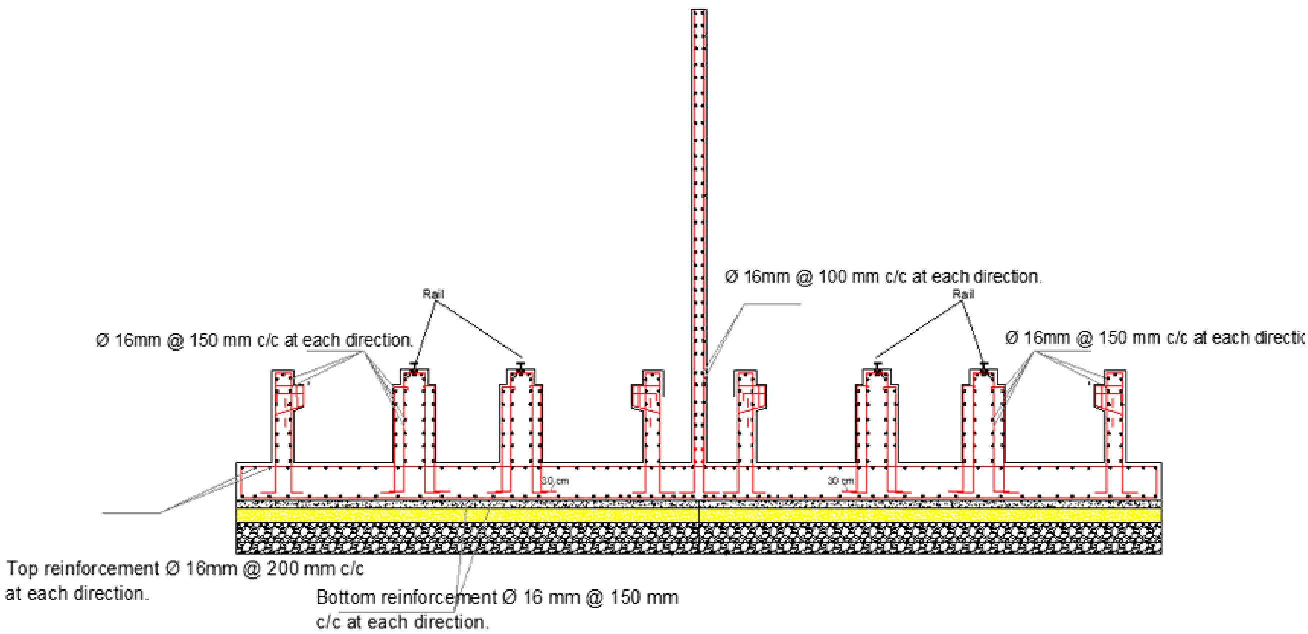

Figure 12. The whole design of transformers foundation

After conducting all steps, the analysis and the design of raft foundation, beams under the transformer and the fire wall. It is desire to explain the full sketch of the reinforcement for all parts in details.

Using the finite elements analysis using structural software for structural analysis and design of structures is considerable safe to in finding the reinforcements and structural requirement.

The whole design of the raft foundation and the beams with retaining walls are shown in Figure 12.

5. CONCLUSIONS

The FEM models were carried out to analysis and designs a footing with all structural requirements for two neighbor transformers. The foundation was checked for geotechnical requirement to be safe in soil shear failure and settlement damage.

There are some points may be drawn as following:

1-The results of conventional equations or analytical methods to check the immediate settlement are seemed to be compatible for results from analysis of finite element.

2-The obtained results from finite element method analyses gave generally coincidence with conventional equations to calculate the reinforcement's areas for all structural parts as shown in Table 5.

3-The analysis of finite element using structural program gives acceptable results for reinforcement, shear and moment results.

4-The finite element analysis gives comfortable way to alter the properties, dimension of the structural part and adding the wind and seismic loads.

5-Using the FEM provide time saving to conduct the analysis and design in different situation of loading.

REFERENCES

[1] Al-Jeznawi, D., Al-Azzawi, A.A. (2021). The behavior of strip footing resting on soil strengthened with geogrid. Civil and Environmental Engineering, 17(2): 597-609. https://doi.org/10.2478/cee-2021-0060

[2] Magbool, H.M., El-Abbasy, A.A. (2021). Finite element verification of the unreliability of using structural plain concrete footing under reinforced concrete footing. Case Studies in Construction Materials, 15: e00734. https://doi.org/10.1016/j.cscm.2021.e00734

[3] Ekbote, A.G., Nainegali, L. (2021). Finite element analysis of two nearby interfering asymmetric footings embedded in cohesionless foundation medium. Geomechanics and Geoengineering, 16(4): 263-276. https://doi.org/10.1080/17486025.2019.1664776

[4] Loukidis, D., Salgado, R. (2009). Bearing capacity of strip and circular footings in sand using finite elements. Computers and Geotechnics, 36(5): 871-879. https://doi.org/10.1016/j.compgeo.2009.01.012

[5] Zedan, A.J., Maulood, H.J. (2017). Pressure-settlement characteristics of shallow foundations using finite element method. Tikrit Journal of Engineering Sciences, 24(1): 25-37. https://doi.org/10.25130/tjes.24.2017.03

[6] Khalil, A.A., Alzaidy, M.N., Kazzaz, Z.A. (2019). Bearing capacity of strip footing on lime stabilized expansive clayey soil. Tikrit Journal of Engineering Sciences, 26(3): 43-50. https://doi.org/10.25130/tjes.26.3.06

[7] Tank, Y.R., Tank, A.R., Dhameliya, H.K. (2016). Dynamic analysis of single cylinder compressor block foundation using SAP: 2000 VS. 16. International Journal of Engineering and Technology, 33(7): 323-327.

[8] Liu, Z. (2013). Design of foundations for large dynamic equipment in a high seismic region. In Structures Congress 2013: Bridging Your Passion with Your Profession, Pennsylvania, United States, pp. 1403-1414. https://doi.org/10.1061/9780784412848.124

[9] Annually, R.I. (1995). ASTM standards. International Standards Worldwide.

[10] Das, B. (2011). Principals of foundation engineering. Library of Congress Control Number: 2010922634, USA.

[11] Budhu, M. (2010). Soil Mechanics and Foundations. John Wiley and Sons.

[12] Briaud, J.L. (2023). Geotechnical Engineering: Unsaturated and Saturated Soils. John Wiley & Sons.

[13] BNBC 2020. (2021). Bangladesh National Building Code.: Part 6, Chapter 2, Section 2.4. https://mccibd.org/wp-content/uploads/2021/09/Bangladesh-National-Building-Code-2020.pdf.

[14] Das, B.M., Sivakugan, N. (2017). Fundamentals of Geotechnical Engineering. Cengage Learning.

[15] Bowles, J.E. (1996). Foundation Analysis and Design. McGraw-Hill, New York.

[16] Potts, D.M., Zdravković, L., Addenbrooke, T.I., Higgins, K.G., Kovačević, N. (2001). Finite Element Analysis in Geotechnical Engineering: Volume Two-Application. London: Thomas Telford, p. 427. https://doi.org/10.1680/feaigea.27831.fm

[17] ACI Committee, 3. (2008). Building code requirements for structural concrete (ACI 318-08) and commentary. American Concrete Institute.

[18] SAP 2000 Manual. (1995). Structural Analysis Program Manual, Computer and Structure. Inc., Berkeley, USA.

[19] Alzubaidi, R., Husain, H.M., Shukur, S. (2023). Finite-element analysis of beam resting on footing. GEOMATE Journal, 24(105): 26-32.

[20] Acharyya, R., Dey, A. (2017). Finite element investigation of the bearing capacity of square footings resting on sloping ground. INAE Letters, 2: 97-105. https://doi.org/10.1007/s41403-017-0028-6

[21] Loukidis, D., Salgado, R. (2009). Bearing capacity of strip and circular footings in sand using finite elements. Computers and Geotechnics, 36(5): 871-879. https://doi.org/10.1016/j.compgeo.2009.01.012

[22] Huat, B.B., Mohammed, T.A. (2006). Finite element study using FE code (PLAXIS) on the geotechnical behavior of shell footings. Journal of Computer Science, 2(1): 104-108.

[23] Likitlersuang, S., Chheng, C., Keawsawasvong, S. (2019). Structural modelling in finite element analysis of deep excavation. Journal of GeoEngineering, 14(3): 121-128. https://doi.org/10.6310/jog.201909_14(3).1