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Finite Element Analysis of Well Pads in Basra Province

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Abstrac: After the year 2003, the oil / gas sector evolved and gained investment. International companies of different origins utilized heavy drilling rigs (to achieve high drilling depths) and entered our region. Meanwhile, some drilling problems were recorded, accompanied by well-pad failure cases. This research aims to study the behavior of well-pads with different geometric configurations, under the effects of drilling rigs with various characteristics, within the Basra province. Four case studies have been selected to represent four fields, namely: Siba, Zubair, West Qurna-2, and Zubair-Mishrif fields. The finite element method is utilized to conduct a stress analysis process, adopting an elastic–plastic constitutive relation for soil, based on Drucker-Prager's yield criterion. The maximum contact pressure applied on soil (under the working loads) is compared to its bearing capacity. When a rigid method is used to calculate the contact pressure, it is compared with the ultimate soil-bearing capacity, as calculated by Reddy and Srinivasan's method for cohesive soils, with allowable bearing capacity taken from the Peck, Hanson, and Thornburn's method for cohesionless soils. The contact pressure calculated via the finite element method is compared with the ultimate soil-bearing capacity calculated using the same method, based on a settlement of 50 mm. The extreme values of the bending moments and shear forces developed in the well-pad sections (under the factored loads), are compared with the section capacities calculated by using the ultimate strength design method. Regarding the geotechnical side, the results indicate insufficient safety factors against soil shear failure for some cases, especially for cohesive soil profiles. For cohesionless soil profiles, the provided safety factors are sufficient. The finite element method reveals higher contact pressures compared to the conventional rigid method. For cohesionless soil profiles, the Peck, Hanson, and Thornburn's method, gives a bigger safety margin than the finite element method. The immediate settlement values are almost tolerable. Regarding the structural side, it has been identified that a uniform section is adopted for all locations of each pad, for individual wells. In most cases, the provided reinforcing steel is less than the minimum code requirement. This leads to a violation of the section capacity of bending, at least near the cellar. The beam shear capacity is rarely violated. Using strip footings beneath the rig skids, permits utilizing a heavy section that satisfies the requirements of structural safety, without violating the economic considerations.

التحليل بالعناصر المحددة لقواعد الآبار في مقاطعة البصرة

حيدر سعد الجبير ،هبة عبد الحسين صاحب

الخلاصة: بعد عام (2003 م) ، شهد قطاع النفط / الغاز إستثماراً متنامياً ، حيث دخلت إلى منطقتنا شركات عالمية ذات أصول مختلفة ، سخرت أبراج حفر ثقيلة (لتحقيق أعماق حفر كبيرة). في تلك الأثناء سجلت بعض مشاكل حفر ، ترافقت معها حالات فشل لقواعد الآبار
يهدف البحث إلى دراسة تصرف قواعد آبار ذات معالم هندسية مختلفة ، تحت تأثيرات أبراج حفر ذات خصائص متنوعة ، ضمن مقاطعة البصرة.تم إختيار أربع حالات للدراسة لتمثل أربعة حقول ، بالذات: حقول السيبة ، الزبير ، غرب القرنة2 و الزبير- مشرف.سخرت طريقة العناصر المحددة لتنفيذ عملية تحليل الإجهادات،بتبني علاقة تكوينية مرنة - لدنة للتربة تستند إلى قاعدة إذعان دروكر –بريغر (Drucker-Prager)
قورن ضغط التماس الأقصى المسلط على التربة(تحت الأحمال العاملة) مع قابلية تحملها. عند إستخدام الطريقة الجاسئة لحساب ضغط التماس ، فقد قورن مع قابلية التحمل القصوى المحسوبة من طريقة ريدي و سرينيفاسان(Reddy and Srinivasan) للترب المتماسكة و قابلية التحمل المسموحة المحسوبة من طريقة بيك وهانسون وثورنبيرن (Peck, Hanson, and Thornburn) للترب غير المتماسكة. ضغط التماس المحسوب بواسطة طريقة العناصر المحددة ، قورن مع قابلية التحمل القصوى من ذات الطريقة ، إستناداً لهبوط قدره(50 ملم). القيم المتطرفة لعزوم الإنحناء وقوى القص المتولدة في مقاطع قواعد الآبار(تحت الأحمال المكبرة) ، قورنت مع سعات المقاطع ، وكما حسبت من طريقة الجهد الأقصى.بالنسبة للجانب الجيوتقني ، أشرت النتائج معاملات أمان غير كافية ضد الفشل القصي للتربة لبعض الحالات ، وعلى وجه الخصوص لقطاعات تربة متماسكة. لقطاعات تربة غير متماسكة ، فإن معاملات الأمان الموفرة كانت كافية.عكست طريقة العناصر المحددة ضغوط تماس أعلى مقارنة بالطريقة الجاسئة الشائعة. لقطاعات التربة غير المتماسكة أعطت طريقة بيك وهانسون و ثورنبيرن هوامش أمان أكبر من طريقة العناصر المحددة. قيم الهبوط الآني كانت على الأغلب مقبولة. بالنسبة للجانب الإنشائي ، لوحظ تبني مقطع منتظم لجميع مواقع كل قاعدة ، للآبار المنفردة. في أغلب الحالات كان حديد التسليح الموفر أقل من متطلبات الحد الأدنى للمدونة. لقد أدى ذلك إلى خرق سعة المقطع للإنثناء ، على الأقل قرب القبو(Cellar) . سعة قص العتبة نادراً ما تم خرقها. إستخدام أسس شريطية تحت مزلقات البرج ، يسمح بتسخير مقطع كبير يستوفي متطلبات الأمان الإنشائي ، دون خرق الإعتبارات الإقتصادية.

2. Introduction

A well site is a plot of land that is used to accommodate a drilling rig along with the necessary supporting services, including water and waste storage, drill-pipe storage, field-services equipment, motor-vehicle parking, and temporary office buildings [1].

The major components of each individual well site are:

- A level drilling area for placement and support of the drilling rig and related equipment, production facilities, and storage tanks.
- An earthen reserve pit to contain drilling fluids, drilled cuttings, and fluids produced during the drilling operation.
- An earthen flare pit for the safe ignition of flammable gases produced during testing and production operations. The study was conducted on some pads in oil or gas fields in the Basra province, south of Iraq. These fields are: Siba gas field, which is located about 30 km south-east of Basra city. The field is approximately 21 km long and 6–13 km wide. It was explored in 1968 and has a reserve of 1.1 trillion cubic feet [2].
- Zubair oil field, which is one of the largest fields in the world, is located west of Basra. The field is approximately 65 km long and 18 km wide. It was discovered by the Basra Petroleum Company, an associate of the Iraq Petroleum Company, in 1949. It has 4.5 billion barrels of proven reserves [3].
- West Qurna 2 oil field. It is one of Iraq's largest oil fields, which covers an area of 340 km^2. The estimated recoverable reserves of the field are 14 billion barrels of oil, making it the second largest undeveloped field in the world [4].
- Zubair Mishrif oil field is located in the Basra province, about 16.82 km from Basra city [5].

Pads are classified depending on the number of wells that can be drilled on them, as single well pads, multi well pads (cluster), or depending on the material used for their construction, such as, reinforced concrete mat, gravel pads, wooden mat, rig mat sprayed with polyurea systems).

3. THEORETICAL BACKGROUND

3.1 Soil-Bearing Capacity for Raft Foundations

The minimum pressure applied by the foundation that causes shear failure in the supporting soil is called the ultimate bearing capacity [6].

3.1 .1 Cohesive soils

The ultimate net bearing capacity is calculated as:

$$(q_{ult})_{net}=5.14c_u(1+s_c'+d_c') \qquad (1)$$

q_{ult}: Ultimate bearing capacity

c_u: Undrained cohesions of the soil

S_c': Dimensionless shape factor = 0.2 B/L. d_c': dimensionless depth factor. $d_c' = 0.4\kappa$,

$\kappa = D_f/B$ for $D_f/B \le 1$,

$\kappa = \tan^{-1}(D_f/B)$ for $(D_f/B)>1$.

D_f: Footing embedment depth

B: Footing width, L: footing length

Another approach is by adopting the Reddy and Srinivasan's method for foundations on two-cohesive layers under undrained conditions [7]:

$$(q_{ult})_{net} = c_{u1} N_c (1+s_c'+ d_c') \qquad (2)$$

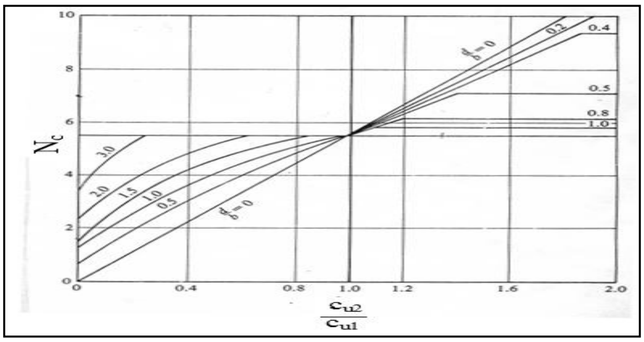

Figure 1: Nc-values for a two-layer system (φ = 0) conditions

c_{u1},c_{u2}: Undrained cohesions of the first and second layers, respectively.

N_c: Bearing capacity factor.

d: Depth to the upper surface of second layer, measured from the foundation level.

b: B/2.

A combination of the methods was used to calculate the most critical value.

3.1.2 Cohesionless soils

The bearing capacity equations give high values for foundations having large widths (B-value), such as, raft foundations. Peck, Hanson, and Thornburn's method was adopted to calculate the bearing capacity based on the results of the standard penetration test (SPT) [8], Figure 2.

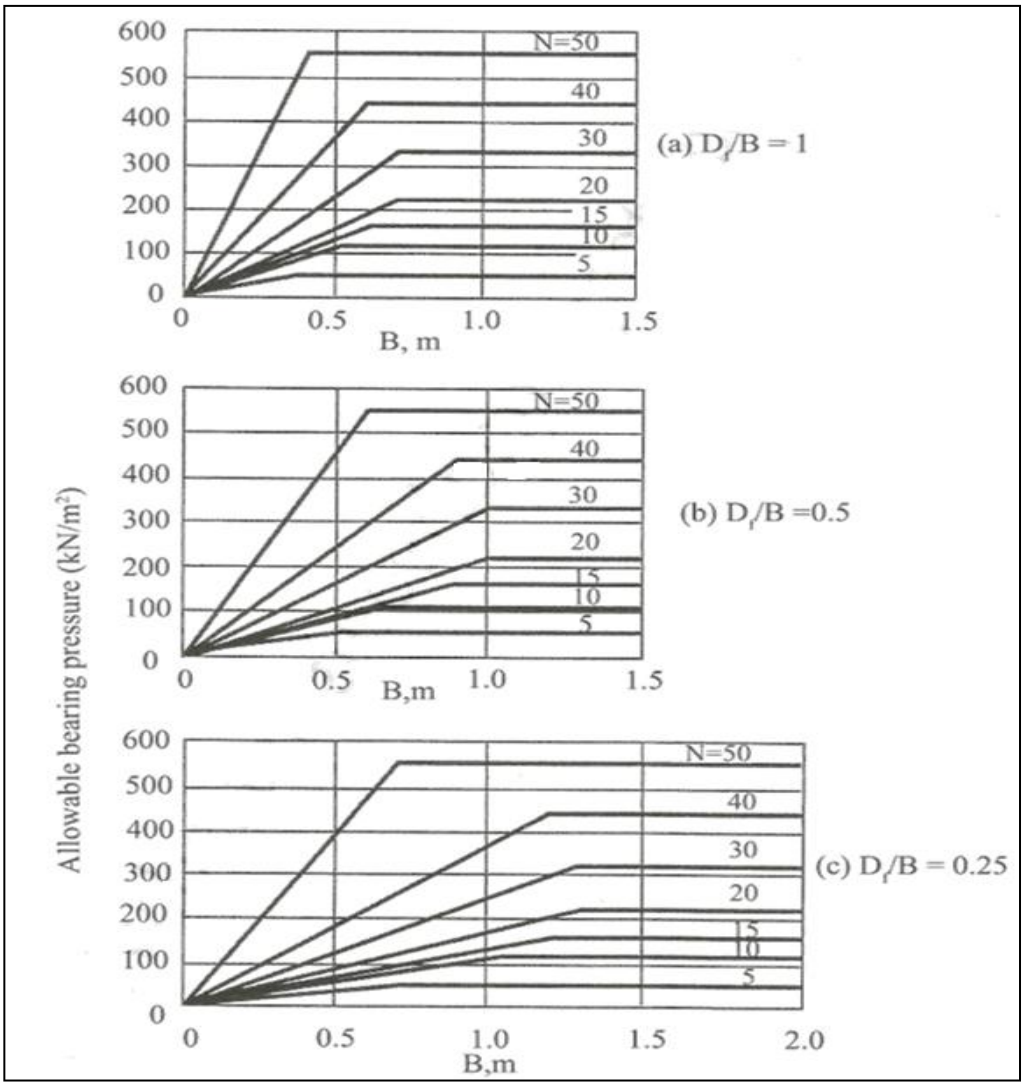

Figure 2: Design chart for proportioning footings on sand [8]

3.2 Bearing capacity by the Finite Element Method

The finite element method (FEM) can be used to estimate the ultimate bearing pressure, by analyzing the foundation under increasing load. Soil failure is detected when the numerical solution does not achieve convergence. Also, the failure load can be taken as the load causing specified maximum settlement.

3.3 Foundation Settlement

The immediate (elastic) settlement is calculated under the applied working load simultaneously during the analysis by the FEM. With regard to the consolidation settlement, it is not taken into consideration due to the short loading period.

3.5 Pile-Raft Foundation

This type of foundation is adopted when the raft foundation does not meet the bearing capacity and/or settlement requirements. The pad is treated as a plate resting on an elastic continuum (the soil) and discrete springs (the piles).

4. STRESS ANALYSES VIA THE FINITE ELEMENT METHOD

As the structure is composed of several finite elements, the individual element stiffness matrices and load vectors are to be assembled in a suitable manner and the overall equilibrium equations have to be formulated as in [Rao]:

$[\underline{K}]\vec{\underline{Q}} = \vec{\underline{P}}$ (3) ……(4.7)

Where:

$[\underline{K}] = \sum_{e=1}^{n}[K^{(e)}]$ (4)

$[\underline{K}]$ = global stiffness matrix

$\vec{\underline{Q}}$ = global vector of nodal displacements

$\vec{\underline{P}}$ = global nodal load vector

In this research, concrete is treated as an elastic material and the soil is treated as an Elasto-plastic material modeled by the Drucker-Prager yield function**.**

1. 5. ANALYSES AND RESULTS

For each case, the geotechnical analysis is performed under the working loads, whereas, the structural analysis is performed under the ultimate loads resulting from multiplying dead loads by 1.4 and live loads by 1.7, according to the ACI-Code 318-95. The theory of flexure was utilized to transmit the rig loads to the concrete pad. The responses of the foundation systems were presented in terms of the generated displacement fields, in addition to the internal reactions represented by shear forces, bending moments, and torques in the concrete pad.

5.1 Siba Gas Field

The site of a well pad (5) is considered is a typical case of this field. The geotechnical data of the site is taken from [Engineering Consulting Bureau - college of engineering - University of Basra]. Table 1 shows the concrete pad properties. The drilling rig (of Chinese origin) used applies an eccentric load of 10906 kN. Figure 3 illustrates the general layout of the concrete pad with supporting skids and shows the distribution of loads transmitted to the pad.

The contours of vertical displacement under the ultimate loads are shown in Figure 4. Figures 5 and 6 illustrate the contours and response values in terms of bending moments.

Table 1 Pad properties for Siba-5 site

Parameter	Symbol	Unit	Description/ Value
Material Model	-	-	Linear-Isotropic
Thickness	t	m	1
Plan dimensions	B* L	m	14*20.5
Modulus of elasticity E	E	MPa	23500
Poisson ratio	v	-	0.2
Unit weight	γ	kN/m^3	25
Specific concrete compressive strength	f_c'	MPa	25
Yield strength of reinforcing steel	f_y	MPa	413
Reinforcement details	-	-	3-layeres of ϕ*16mm@150mm* *in both* directions

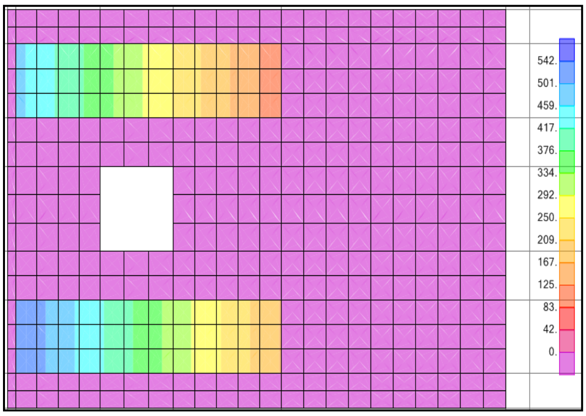

Figure 3 Factored load (kN/m^2) distribution of the Chinese rig in Siba-5 gas field.

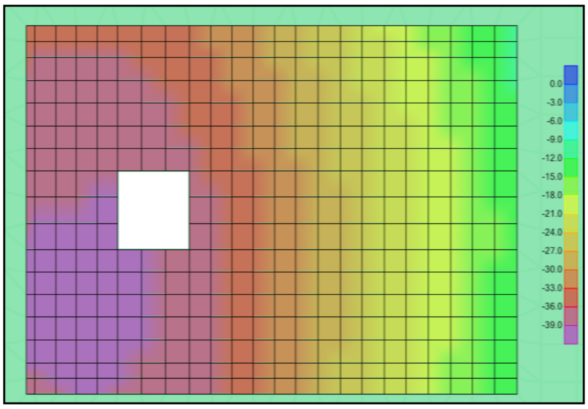

Figure 4 Contours of vertical displacement (mm) due to working loads (Siba-5)

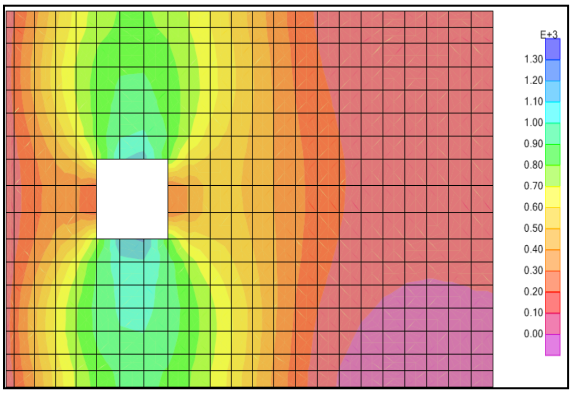

Figure 5 Contours of the bending moment (kN.m/m) in x-direction due to factored loads (Siba-5)

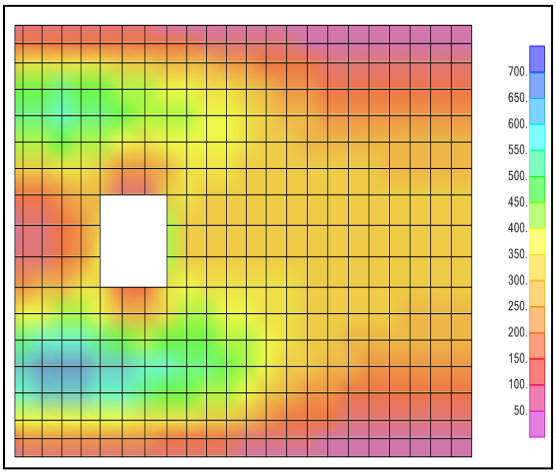

Figure 6 Contours of the bending moment (kN.m/m) in Y-direction due to factored loads (Siba-5)

5.2 Zubair Oil Field

The geotechnical data of the site is drawn from [Engineering Consulting Bureau - college of engineering - University of Basra]. Table 2 lists the concrete pad properties. The super structure is an Italian rig, which transfers its load to the pad by its skids, the applied load in case 1 consists of the operation load plus a pressure due to 59.264 km/hour wind blowing from the right side. The pressure distributions are shown in Figure 7. The distribution of vertical displacement around the cellar is shown in Figure 8 while Figures 9 and 10 show the distribution and values of shear forces.

Table 2 Pad properties for the Zubair site

Parameter	Symbol	Unit	Description/ value
Material Model	-	-	Linear-Isotropic
Thickness	t	m	0.8
Dimension	B*L	m	15*30
Modulus of elasticity E	E	MPa	23500
Poisson ratio	ν	-	0.2
Unit weight	γ	kN/m^3	25
Specific concrete compressive strength	f_c'	MPa	25
Yield strength	fy	MPa	413
Reinforcement details	-	-	2-layers of ϕ *16@200 mm* top and bottom in both directions

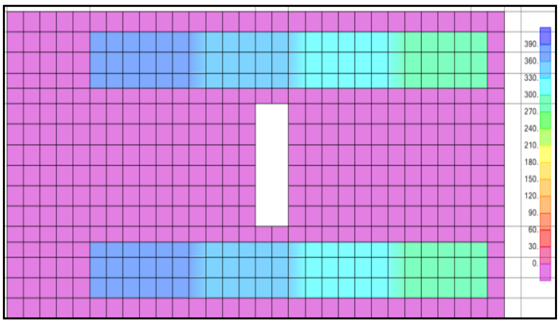

Figure 7 load distribution of Italian rig in Zubair site (case -1)

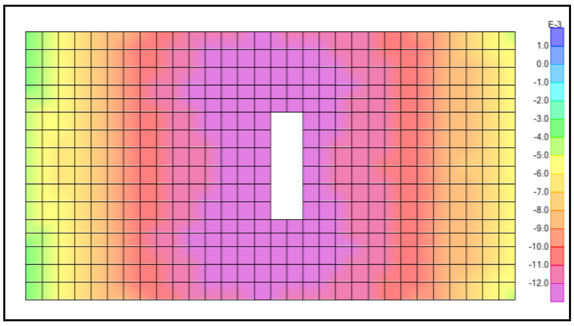

Figure 8 Contours of vertical displacement (mm) due to working loads (Zubair case -1)

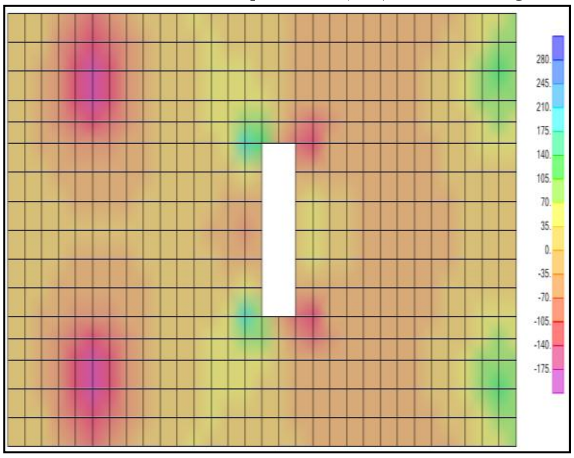

Figure 9 Resultant shear force (kN/m) in xz direction diagram due to factored loads (Zubair case -1)

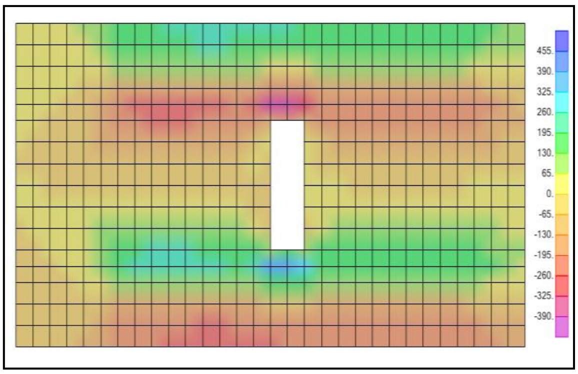

Figure 10 Resultant shear force (kN/m) in yz-direction diagram due to factored loads (Zubair case -1)

In case 2, the applied load consists of the operation load plus the pressure due to a 59.264 km/hour wind blowing from the left side. The pressure distribution and magnitudes are shown in Figure 11. The distribution of vertical displacement around the cellar is shown in Figure 12, even as Figures 13 and 14 show the distribution and values of the shear forces.

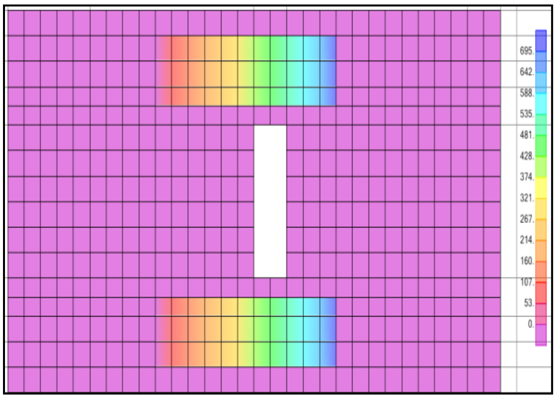

Figure 11 Load distribution (kN/m^2) of Italian rig in Zubair site (case-2)

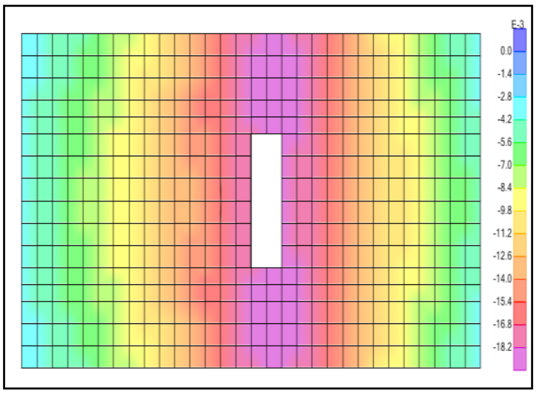

Figure 12 Contours of vertical displacement (mm) due to working loads (Zubair case -2)

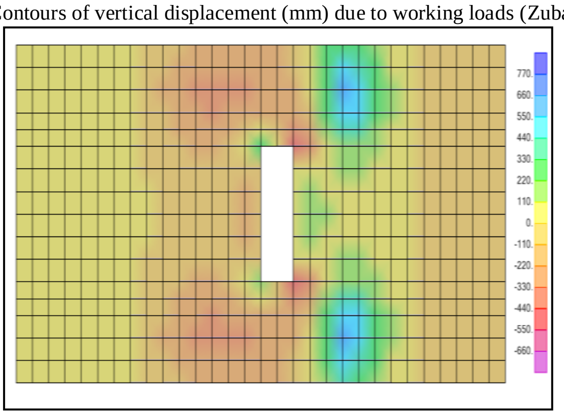

Figure 13 Resultant shear force (kN/m) in xz-direction diagram due to factored loads (Zubair case-2)

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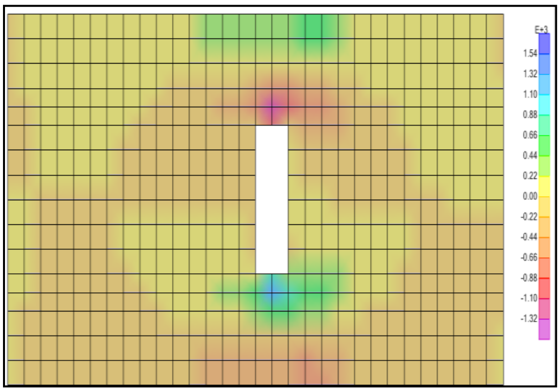

Figure 14 Resultant shear force (kN/m) in yz-direction diagram due to factored loads (Zubair case -2)

5.3 West Qurna-2 Oil Field

Site (Cluster 5) is taken as a case study of this field. The geotechnical data of the site is taken from [Amir F. Ibrahim]. The concrete pad properties are illustrated in Table 3.

Table 3 Pad properties for West Qurna-2 site

Parameter	Symbol	Units	Description/value
Material Model	-	-	Linear-Isotropic
Thickness	t	m	0.85
Dimension	B * L	m	3.74 *193 for each side
Modulus of elasticity E	E	MPa	23500
Poisson ratio	v	-	0.2
Unit weight	γ	kN/m^3	25
Specific concrete compressive strength	f_c'	MPa	25
Yield strength of reinforcing steel	f_y	MPa	413
Reinforcement details	-	-	*ϕ20 @ 160 mm top* (x-direction) *ϕ25 @ 160 mm* bottom (x-direction) *ϕ20 @ 200 mm* top and bottom (Y- direction)

The drilling rig used was of Chinese origin, moving on a cluster to drill twelve wells, with an applied load of 11217.4 kN with the distributions shown in Figure 15. Figure 16 shows the distribution of the immediate settlement below the foundation, under the working loads, even as Figure 17 shows the resultant torsion diagram due to factored loads.

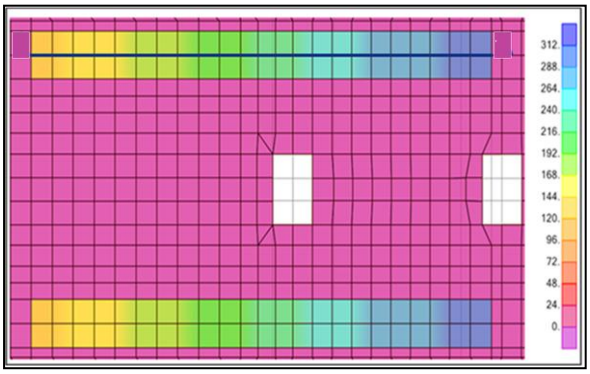

Figure 15 Load distribution (kN/m^2) of Chinese rig in West Qurna-2 site

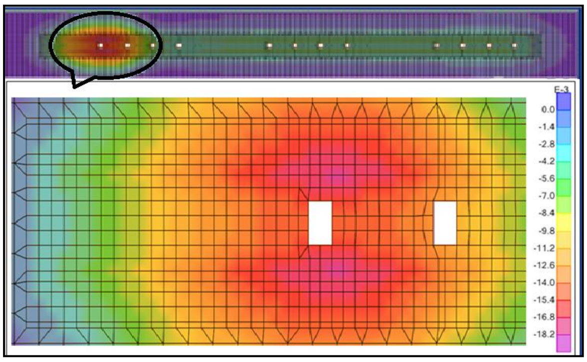

Figure 16 Contours of vertical displacement (mm) due to working loads (West Qurna-2)

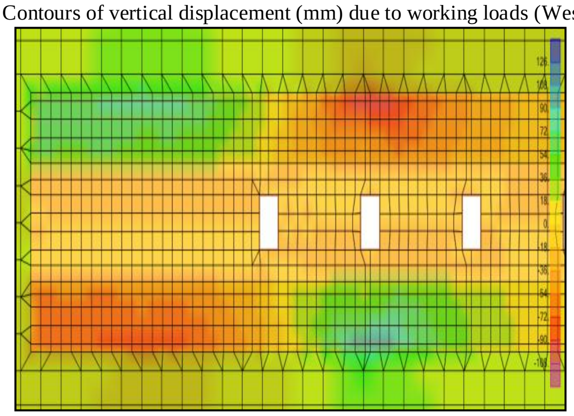

Figure 17 Resultant torsion (kN.m/m) diagram due to factored loads (West Qurna-2)

5.4 Zubair Mishrif Oil Field

The geotechnical data of the site is drawn from [Engineering Consulting Bureau - college of engineering - University of Basra]. Table 4 lists the concrete pad properties. The pad layout for the Halliburton rig and the distribution of loads transmitted to the pad are shown in Figure 18. Figure 19 show the contours of vertical displacement due to working loads, even as Figure 20 explains the contours of vertical stresses due to working loads.

Table (4) Pad properties for Zubair Mishrif site

Parameter	Symbol	Unit	Description/ value
Material Model	-	-	Linear-Isotropic
Thickness	t	(m)	0.6
Dimension	B* L	(m)	14*28
Modulus of elasticity E	E	MPa	23500
Poisson ratio	v	-	0.2
Unit weight	γ	kN/m^3	25
Specific concrete compressive strength	f_c'	MPa	25
Yield strength for reinforcing steel	f_y	MPa	413
Reinforcement details	-	-	Two layers of *ϕ16@200 mm* top and bottom in both direction

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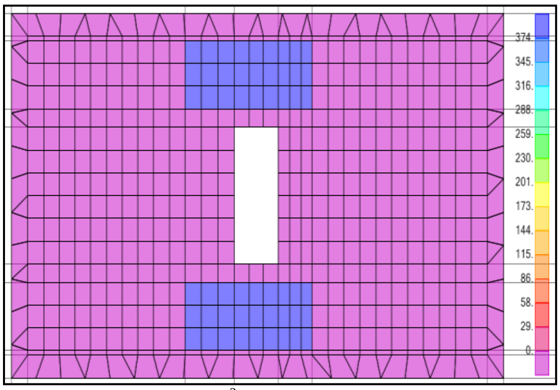

Figure 18 Factored loads (kN/m^2) of the American rig in Zubair Mishrif site

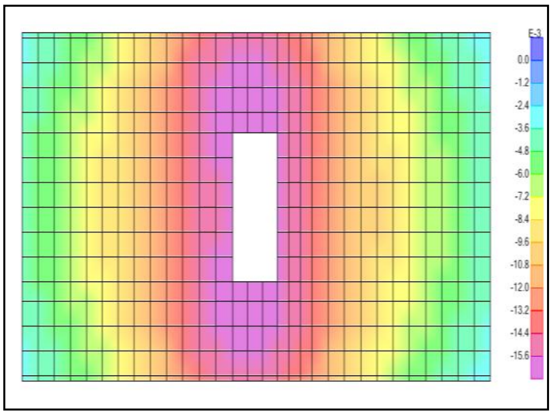

Figure 19 Contours of vertical displacement (mm) due to working loads (Zubair Mishrif)

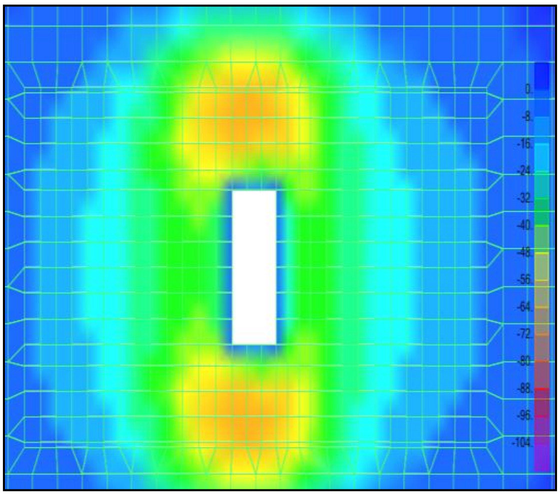
Figure (20) Contours of vertical stresses (kN/m^2) due to working loads (Zubair Mishrif)

6.Summary of results

The results of geotechnical analyses are summarized in Table 5 and the results of structural analyses are summarized in Table 6

Table 5 Summary of the geotechnical analyses [under working loads]

Well-pad	Conventional				Finite Element Method			
	Bearing capacity kPa		$(q_{app})_{max}$ kPa	F_s	q_{ult} kPa	$(q_{app})_{max}$ kPa	F_s	Settl. mm
Siba -5	q_{ult}	170.49	111.49	1.53	490	331	1.48	39.8
Zubair (case -1) (case -2)	q_{all}	475 475	75.46 70.11		960 2150	131 222	7.3 9.6	13 18
West Qurna -2	q_{ult}	176	50	3.52	640	94	6.80	18
Zubair Mishrif	q_{all}	300	46.40		450	105	4.3	17

Table 6 Summary of the structural analyses [under factored loads]

Well-pad	$B.M._{max}$	$\rho_{furnished}$	$B.M._{resist.}$	V_{max}	$V_{resist.}$
Siba -5	1217	0.00157	475.8	499.4	579.5
Zubair (case -1) (case -2)	348 1146	0.00147 0.00147	261.0 261.0	421 1130	452.0 452.0
West Qurna -II	375.5	0.00389	766.9	211	473.3
Zubair Mishrif	509.3	0.00197	186.5	564	324.49

6. Conclusions

The conduction of this research regarding reinforced concrete well-pads at various fields in the Basra province produced the following conclusions associated with different design policies adopted by international companies:

1. The geotechnical investigation program does not take it to its full extent, where there is still some shortage regarding the number of boreholes and sampling processes of soft soils.
2. The provided safety factors against soil shear failure are not sufficient in some instances, especially for cohesive soil profiles. For cohesionless profiles, the available safety factors are usually sufficient.
3. The maximum contact pressure values applied, under working loads, which resulted from the finite element analyses, exceed those of their counterparts, as calculated based on the traditional rigid method.
4. For cohesionless soil profiles, the safety margins against soil shear failure, according to Peck, Hanson, and Thornburn's method, are 1.7, 1.4, and 3.0 times those calculated via the finite element method, based on a specified settlement, for Zubair and Zubair Mishrif loading cases, respectively.
5. The immediate settlement values were, in general, within acceptable limits.
6. For individual wells, it is common practice to adopt a uniform section (thickness and reinforcement) at all locations of the pad.
7. In most cases, the provided reinforcing steel for bending is less than the minimum code's requirements. The provided ratios are 0.46, 0.43, and 0.58, the minimum required values for Siba-5, Zubair, and Zubair Mishrif pads, respectively.
8. In many cases, the section capacity of bending is violated at least at narrow regions near the cellar.
9. On an odd occasion, the section capacity in the beam shear is violated.
10. Utilizing strip footings under the skids, permits using heavy sections to satisfy the requirements of structural safety, without violating the economic considerations.

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NOMENCLATURE

Symbol	*Description*	*unit*
B	*footing width*	*m*
b	*B/2*	*m*
c_u	*undrained cohesions of the soil.*	*kPa*
c_{u1}, c_{u2}	*undrained cohesions of the first and second layers, respectively.*	*kPa*
D_f	*footing embedment depth*	*m*

d	*depth to the upper surface of second layer, measured from foundation level*	*m*
d_c'	*depth factor*	
E	*Modulus of elasticity*	*MPa*
f_c'	*cylinder ultimate compression strength of concrete*	*MPa*
$[K]$	*global stiffness matrix*	
$[K^{(e)}]$	*elements stiffness matrix*	
L	*footing length*	*m*
N	*standard penetration number*	*blow*
N_c	*bearing capacity factor*	
n	*number of elements*	
$\underline{\vec{P}}$	*global nodal load vector*	
q_{ult}	*ultimate bearing capacity*	*kPa*
v	*Poisson's ratio*	
vc	*Poisson's ratio of concrete*	
vs	*Poisson's ratio of soil*	
ϕ	*friction angle of soil*	*degree*