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DETERMINATION THE STORY LATERAL DISPLACEMENT AND VERTICAL SETTLEMENT IN RAFT FOUNDATION OF MULTI-STORY BUILDING BY MULTI-LINEAR REGRESSION

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ABSTRACT

Determination the story lateral displacement and vertical settlement in raft foundation of multi-story building are critical especially with presence of effect the soil bed where they are working together as phenomena of soil structure interaction .in this paper a three type of soil in addition to wide range of raft foundation thickness (from 0.3 to 1.3 m) are used to represent the foundation system in addition to reinforcement concrete buildings consisting of 4 stories up to 12 stories with spacing columns of (5m, 6m and 7m) subjected to different types of loading related to the gravity load and lateral loads (seismic and wind load) as results from this variations in cases and parameters a more than 300 models are used in this study which induce a thousands of results by using finite package to obtain a database which are used to fulfilment the goal of this study, a good results was obtained , where coefficient of , r and r^2 are equal to 0.9 and 0.81 respectively in case of vertical settlement in the raft foundation due to different type of loading .0.98 and 0.95 represent the r and r^2 respectively for the story lateral displacement due to wind load finally the r and r^2 are equal to 0.84 and 0.71 respectively in case story lateral displacement due to the seismic action.

Keywords: multi-storey building, soil modelling, superstructure, linear regression.

INTRODUCTION

Raft foundation usually used for different types of the buildings which can be defined as a large slab used to connect one or group of columns with base soil. Raft foundation is vary in it is own stiffness. according to the raft foundation stiffness the raft are vary from stiff (rigid) to flexible base, in addition to intermediate condition of semi rigid raft foundation. Also it can identifying the degree of rigidity can be determine by using the rigidity factor (K_r) which depend on both, the raft foundation stiffness and the building stiffness (Bowles, 1996). The raft foundation can be consider as flexible member in case the rigidity factor Kr less than 0.5, rigidity factor (K_r) can be express as following:

$$K_r = \frac{EI_b}{E_s B^3} \tag{1}$$

EI_b may be taken as

$$EI_b = EI_f + \sum EI_{b_i} + \sum \frac{Eah^3}{12}$$

Where EI_b =flexural rigidity of the superstructure and mat, *E*= composite modulus of elasticity of superstructure frame
EI_f= footing or mat flexural rigidity
E_S = modulus of elasticity of soil
$\sum \frac{Eah^3}{12}$ =effective rigidity of shear walls perpendicular to B; h=height; a =wall thickness
$\sum EI_{b_i}$ = rigidity of several members making up the frame resistance perpendicular to base width perpendicular to direction which under consideration
B is the base width of foundation perpendicular to direction of interest.

Soil subgrade reaction

Soil reaction under the raft foundation are proportional increase with the settlement of the raft at each point along the footing, where the foundation resting on individual spring has own identical ,independent, linearly and closely spaced for each to other with knowing value of spring stiffness to produce a modulus of subgrade reaction (kips/in^3, kN/m^3, ..etc.), K_s in the vertical direction (z), which are referring to the intensity of the reaction force on foundation pressure and can be obtained by using the plate-load test data. In order to modeling the soil, springs are used to represent the interaction between the soil and the foundation which producing by (Winkler1867) and developed later by (Heteyni, 1967) and (Kerr, 1964), thus this model some time called a Winkler foundation.

$$K_s=q/\delta \tag{2}$$

Where q is the load in force per area, δ is the settlement (Vesic, 1961) suggested another formula to find out the value of the K_S by using the stress-strain modulus as shown in the equation.

$$K_S' = 0.65(E_S B^4/E_F I_F)^{1/12} x(E_S/1-u^2) \tag{3}$$

B, I_F and E_F are the foundation properties (width, moment of inertial and modulus of elasticity respectively) (Bowles, 1996) stated that 'Since the twelfth root of any value multiplied by 0.65 will be close to 1, for all practical purposes the Vesic's equation reduces to

$$K_S' = (E_S/1-u^2) \tag{4}$$

Where the E_S and u are the modulus of elasticity and Poisson's ration for soil respectively. Finally the soil

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subgrade reaction K_S can be expressed as following equation.

$$K_S = K_S^{'}/B \quad (5)$$

Where much software is formulated to analysis such as these problems. It is obviously that the bending not influences much by subgrade reaction in case of rigid raft and versa for the flexible one when bending heavily localized. Thus the flexibility of raft foundation and the soil stiffness in addition to other factors have important role in the behavior of whole structure under different circumstances of loading. During building serviceably life the structure normally subjected to a lot of different type of loading (gravity, wind, snow, seismic …etc) these typesare transfer to raft foundation which in turn transports this loading into soil medium.

Soil structure interaction (SSI)

The effect of raft foundation stiffness in the behavior of multi-story building with penance of the soil medium effect is critical due to the combination of both effects which are known as soil structure interaction (SSI) specially in case of the flexible raft foundation where the deformation occur in foundation raft foundation and the soil medium. Soil are consider as a linear elastic material in case of gravity and wind load while it is behave as non-linear medium in case of earthquakes

ETABS software modeling

The database of this paper which related tothe effect of raft foundation stiffness on behavior of multi-story building by considering a different types of soil and the superstructure feature, was obtained by through application of a finite element method which are used because it is diversity and flexibility as analysis tools with a number of available software by using one of well-known finite element package such as one of an engineering program such as SAP2000, STAAD-PRO, NISA, ANSYS and ETABSx, (NitichKumer and Parveen J.V 2016) in this paper the an engineering software of ETAB2015 are used

Superstructure characteristics

In spite of most of the superstructure elements are comply with ACI 318-14 and FEMA 2009 a variations in raft foundation thickness, number of stories and spacing between columns are used in order to determine the effect of raft foundation stiffness in a different type of buildings which can be summarized in the Table-1.

Table-1. Superstructure feature.

Number of stories	Columns spacing (m)	Raft foundation thickness t_{raft} (m)
4 story	5	0.3,0.4,0.5,0.6
	6	0.3,0.4,0.5,0.6
	7	0.3,0.4,0.5,0.6
	5	0.3,0.4,0.5,0.6
	6	0.3,0.4,0.5,0.6
	7	0.3,0.4,0.5,0.6
	5	0.3,0.4,0.5,0.6
	6	0.3,0.4,0.5,0.6
	7	0.3,0.4,0.5,0.6
6 story	5	0.3,0.4,0.5,0.6,0.7,0.8
	6	0.3,0.4,0.5,0.6,0.7,0.8
	7	0.3,0.4,0.5,0.6,0.7,0.8
	5	0.3,0.4,0.5,0.6,0.7,0.8
	6	0.3,0.4,0.5,0.6,0.7,0.8
	7	0.3,0.4,0.5,0.6,0.7,0.8
	5	0.3,0.4,0.5,0.6,0.7,0.8
	6	0.3,0.4,0.5,0.6,0.7,0.8
	7	0.3,0.4,0.5,0.6,0.7,0.8
8 story	5	0.3,0.4,0.5,0.6,0.7,0.8,0.9
	6	0.3,0.4,0.5,0.6,0.7,0.8,0.9
	7	0.3,0.4,0.5,0.6,0.7,0.8,0.9
	5	0.3,0.4,0.5,0.6,0.7,0.8,0.9
	6	0.3,0.4,0.5,0.6,0.7,0.8,0.9
	7	0.3,0.4,0.5,0.6,0.7,0.8,0.9
	5	0.3,0.4,0.5,0.6,0.7,0.8,0.9
	6	0.3,0.4,0.5,0.6,0.7,0.8,0.9
	7	0.3,0.4,0.5,0.6,0.7,0.8,0.9
10 story	5	0.3,0.4,0.5,0.6,0.7, 0.9,1.0,1.1
	6	0.3,0.4,0.5,0.6,0.7, 0.9,1.0,1.1
	7	0.3,0.4,0.5,0.6,0.7, 0.9,1.0,1.1
	5	0.3,0.4,0.5,0.6,0.7, 0.9,1.0,1.1
	6	0.3,0.4,0.5,0.6,0.7, 0.9,1.0,1.1
	7	0.3,0.4,0.5,0.6,0.7, 0.9,1.0,1.1
	5	0.3,0.4,0.5,0.6,0.7, 0.9,1.0,1.1
	6	0.3,0.4,0.5,0.6,0.7, 0.9,1.0,1.1
	7	0.3,0.4,0.5,0.6,0.7, 0.9,1.0,1.1
12 story	5	0.3,0.4,0.5,0.6,0.7, 0.9, 1.1,1.3
	6	0.3,0.4,0.5,0.6,0.7, 0.9, 1.1,1.3
	7	0.3,0.4,0.5,0.6,0.7, 0.9, 1.1,1.3
	5	0.3,0.4,0.5,0.6,0.7, 0.9, 1.1,1.3
	6	0.3,0.4,0.5,0.6,0.7, 0.9, 1.1,1.3
	7	0.3,0.4,0.5,0.6,0.7, 0.9, 1.1,1.3
	5	0.3,0.4,0.5,0.6,0.7, 0.9, 1.1,1.3
	6	0.3,0.4,0.5,0.6,0.7, 0.9, 1.1,1.3
	7	0.3,0.4,0.5,0.6,0.7, 0.9, 1.1,1.3

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Soil modeling

To represent models the Soil stiffness by equivalent spring stiffness in three dimensions K_x, K_y and K_z for vertical, horizontal and longitudinal in addition to rocking soil stiffness in the aforementioned directions (K_{rx}, K_{ry} and K_{rz}) which represent a 6 degree of freedom (SDOF) at each node (intersection point of two axis in the plane of the raft foundation) by considering Poisson's ratio equal to 0.3 for a different type of soil (Loose, medium and dense soil) as shown in the Figures (5-2) below:

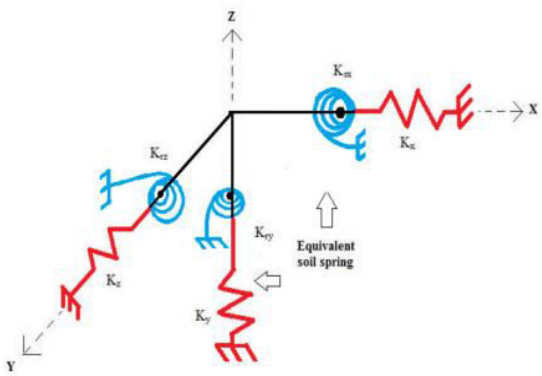

Figure-1. Equivalent spring stiffness (Nitich and Parveen, 2016).

Soil with properties like modulus of elasticity and Passion's ratio in addition to the dimension of the raft foundation are only be needed to calculate the above soil spring to represent the point spring in the program of ETABS software. Where the value of these springs can be calculated according to following formula as appear in the Table-2.

Table-2. Spring stiffness (George Gazet 1991).

Degree of freedom	Stiffness of equivalent soil spring
Vertical	$[2GL/(1-v)](0.73+1.54\chi^{0.75})$
Horizontal (lateral direction)	$[2GL/(2-v)](2+2.5\chi^{0.85})$
Horizontal (longitudinal direction)	$[2GL/(2-v)](2+2.5\chi^{0.85})$-$[0.2/(0.75-v)][GL/(1-(B/L)]$
Rocking about longitudinal	$[G/(1-v)]Ib_x0.75(B/L)0.25[2.4+0.5(B/L)]$
Rocking about lateral	$[G/(1-v)]\ Ib_y0.75(B/L)0.15$
Torsion	$3.5G\ Ib_z0.75(B/L)+0.4(Ibz/B4)0.2$

Where $\chi=Ab/4L^2$, Ab=area of foundation considered, B and L are half -width and half-length of rectangular foundation respectively, Ib_x, Ib_y and Ib_z= moment of inertia of foundation are with respect to longitudinal, lateral and vertical axes respectively by applying the expressions above in addition to some soil properties, the equivalent soil spring at the intersection of the axes in the directions of (X and Y) of the foundation plane can be tabulated as shown in Table-3.

Table-3. Spring stiffness values.

E_s	C.S	K_x	K_y	K_z	K_{rx}	K_{ry}	K_{rz}
10	**5**	**102**	**102**	**125**	**309**	**107**	**1993**
25	5	255	255	312	772	266	4983
50	5	509	509	624	1545	533	9966
10	6	122	122	150	534	184	3444
25	6	305	305	374	1335	460	8610
50	6	610	610	748	2669	920	17221
10	7	143	143	175	848	292	5469
25	7	356	365	437	2119	731	13673
50	7	713	713	873	4283	1462	27346

Where modulus of elasticity (E_s) in units of Mpa of 10, 25 and 50 which related to soil type of loose, medium and dense respectively, while spacing between column (C.S) in unite of meters and the equivalent soil stiffness in kN/m and kN/rad multiplied by 10^3 for displacement and rocking respectively.

Limitations

In this study the earthquake are limited with information of an earthquake which occur in the southern part of Iraq which has magnitude of 5.0 degree (Abd Alridha and Jasem, 2013) which have the following acceleration Figure:

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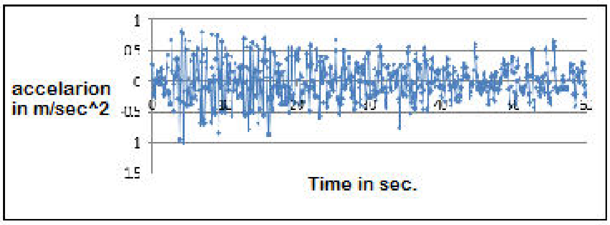

Figure-2. Earthquake acceleration.

While the wind load are specified in 160 km/h, thus due to these limitation earthquake intensity and wind speed are not involved in the equations

CORRELATION AND REGRESSION

Correlation

It is a relationship between two variables. The data can be represented by the order pairs (x,y), where x is the independents variable and y is the dependent variable, there are many type of correlation depended on the relationship type between the aforementioned variables such as negative linear, positive linear, nonlinear and no correlation the measure of the strength and direction of a linear relationship between the variables can by represented by (r) and can be expressed as following:

$$r = \frac{n\sum x.y-(\sum x)(\sum y)}{\sqrt{n\sum y2-(\sum y)2}\,.\sqrt{n\sum x2-(\sum x)2}} \tag{6}$$

REGRESSION

Linear regression

Regression line is the line for which the sum of the squares of the residuals is a minimum; also it is called line of best fit. The expression of regression line for an independent variable x and dependent variable y are as following:

$$Y = a + b.x \tag{7}$$

Where Y is the predicted y- value for a given x-value, (a) represent the intersect value of y and can be expressed as following:

$$a= y^{-} -b.x^{-} \tag{8}$$

y^{-} is the mean of y values while x^{-} is the mean of x values, Finally (b) is the slope of line and can be calculated as following:

$$b = \frac{n\sum xi.yi-(\sum xi)(\sum yi)}{n\sum(xi)2-(\sum xi)2} \tag{9}$$

Multiple linear regressions

Model that contain more than one independent variable are multiple regressions models. A multiple regression model can be expressed as following:

$$Y=b_0+b_1x_1 +b_2x_2 +b_3x_3 +\ldots\ldots\ldots\ldots b_kx_k \tag{10}$$

Where the x_1, x_2, x_3,…..$x_k$are the independent variable , b_0 is the intercept value of y and Y is the dependent variable

Statically works and equations

By using the database which it is represented the results from modeling and analyzing the aforementioned information of multi-story buildings with different features and aspects construct on different type of soil and subjected to different type of loading by using the finite element package of ETABS2015 these database are used to figure out the multi linear regression by using Excel2010, as results of those process an equations were obtained for each case as shown in the next sections.

Generally and in order to applicant these equations a an input data are notation as following:

Ac is the area of columns in (m)
Sc is the spacing between columns in (m)
Es is the soil modulus of elasticity in (mpa)
H is the raft foundation thickness in (m)
N is the total stories number in the building
n is the number of story which under consideration
U is the ultimate dead load multiplied by 0.9

STORY LATERAL DISPLACEMENT

Due to wind load (δ_{wind})

The behavior of multi-story building under wind load can be express as following equation:

δ_{wind} = -0.844 - 42.5*Ac-1.48*Sc - 0.027*Es-5.176*H+3.27*N+1.92*n + 0.2768* U

With R equal to 0.976 and R^2 equal to 0.95 which is represented a good correlation
for example, considering the 4^{th} floor of a 6 story building, column of 0.4x0.4m, spacing between column equal to 5 m, total ultimate of load (0.9*10^3) equal to 44.3kN/m^2 and raft foundation thickness equal to 0.6m resting on loose soil of 10 Mpa modulus of elasticity, in this case the δ_{wind}=13.55 mm (as predicted value of story lateral displacement) while in the actual value according to ETABS2015 this value equal to 12.6mm

Figure-3 represents regression between values in addition to the best fit line

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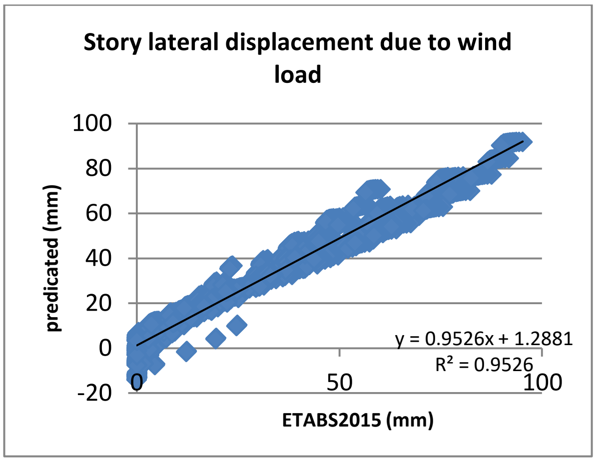

Figure-3. Compassion between predicted and actual story lateral displacement due to wind load.

Due to seismic load ($\delta_{seismic}$)

The behavior of multi-story building (story lateral displacement) due to seismic action can be expressed as shown in the following equation:

$\delta_{seismic}$ = 10.22 + 2.322 *Ac+0.882*Sc-0.00092*Es +0.675*H+ 2.138*n -1.66*N-0.049*U

With R equal to 0.84 and R^2 equal to 0.7 which is represented a good correlation. Considering the3nd floor of 4 story building, column of 0.4x0.4m, spacing between column equal to 5 m, total ultimate of load (0.9*10^3) equal to 32.8kN/m^2 and raft foundation thickness equal to 0.4m resting on loose soil of 10 Mpa modulus of elasticity, in this case the $\delta_{seismic}$ = 13.43 mm (as predicted value of story lateral displacement) while in the actual value according to ETABS2015 this value equal to 14.37mm

Figure-4 represents regression between values in addition to the best fit line

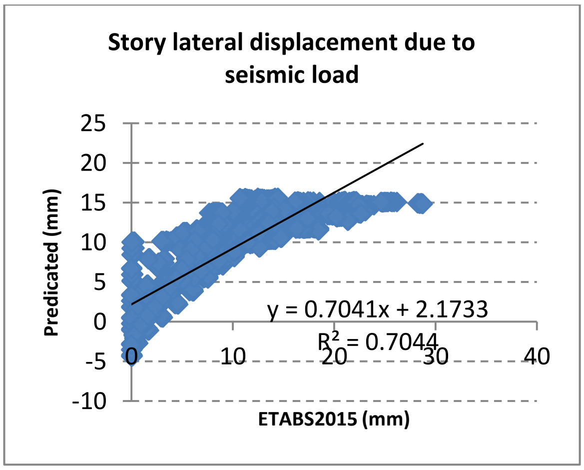

Figure-4. Compassion between predicted and actual story lateral displacement due to wind load.

VERTICAL SETTLEMENT IN THE RAFT FOUNDATION

In this section the center of the raft foundation (C.F) are consider represent the worst case which have the maximum load induced from three type of loading as shown in Figure-5.

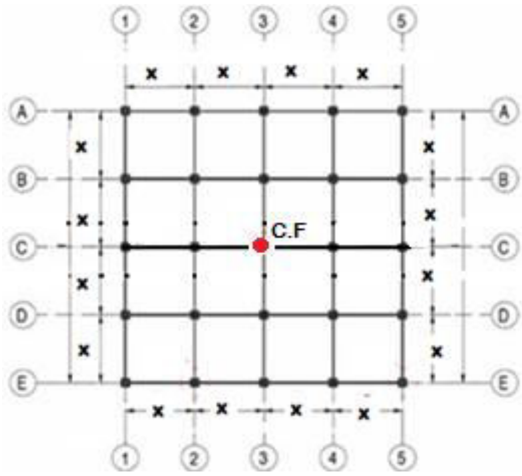

Figure-5. Typical raft foundation.

Due to ultimate gravity load ($\Delta_{gravity}$)

With the same notation above the settlement in the interior column strip can be expressed by following:

$\Delta_{gravity}$ =-26.012-0.81*Ac-0.009*Sc -0.873*Es -3.466*H -0.911*N-.072*U

By considering a 8 story building, column of 0.4x0.4m, spacing between column equal to 5 m, total ultimate of load equal to 111.029 kN/m^2 and raft foundation thickness equal to 0.3m resting on loose soil of 10Mpa modulus of elasticity, in this case the $\Delta_{gravity}$ = -34.32 mm (as predicted value vertical settlement) while in the actual value according to ETABS2015 this value equal to -33mm.

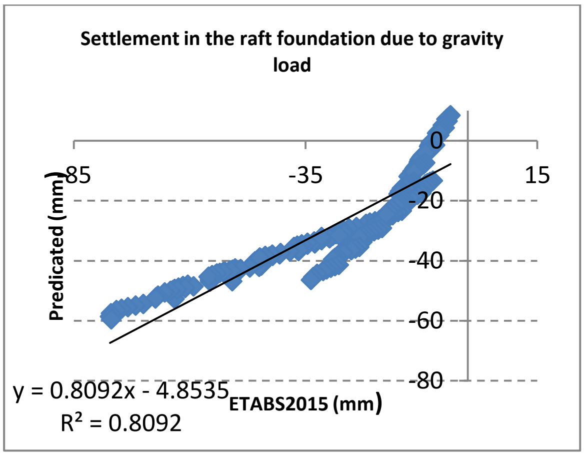

Figure-6. Compassion between predicted and actual settlement in the raft foundation.

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Due to wind load (Δ_{wind})

Δ_{wind} =-18.495 -1.303*Ac-0.125*Sc -0.649*Es -3.443*H -0.67*N-.074*U

For example considering a 6 story building, column of 0.4x0.4m, spacing between column equal to 6m, load of 0.9*D.L equal to 90.046kN/m^2, raft foundation thickness of 0.5m resting on dense soil of 50Mpa modulus of elasticity, in this case the Δ_{wind} = -5.75 mm (as predicted) while in the actual value according to ETABS2015 this value equal to -5.07mm, Figure-13 show regression between values in addition to the best fit line.

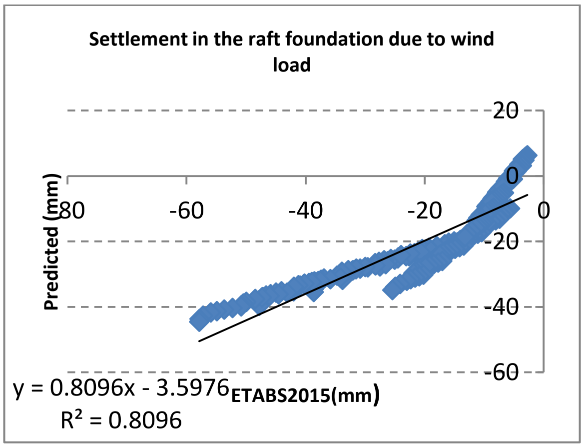

Figure-7. Compassion between predicted and actual settlement in the raft foundation due to wind load.

2.3 Due to wind load ($\Delta_{seismic}$)

The settlement in the interior column strip can be expressed by following equation:

Δ_{wind} = -18.388 -1.264*Ac-0.141*Sc -0.649*Es -3.442*H -0.676*N-.074*U

Considering a 6 story building, column of 0.4x0.4m, spacing between column equal to 5m, load of 0.9*D.L equal to 122kN/m^2 and raft foundation thickness equal to 0.5m resting on loose soil of 10Mpa modulus of elasticity, in this case the $\Delta_{seismic}$ = -27.8 mm (as predicted value vertical settlement) while in the actual value according to ETABS2015 this value equal to -29.94mm.

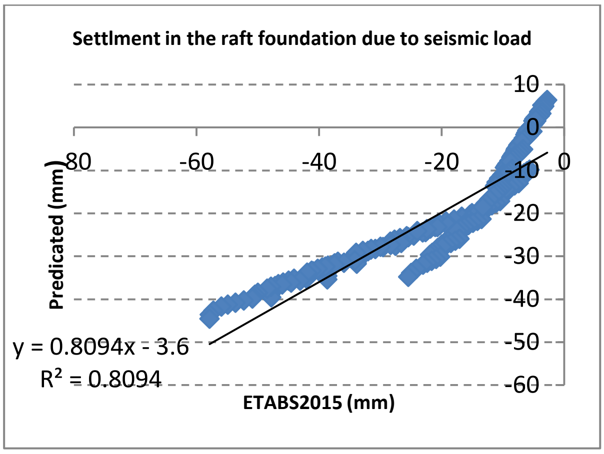

Figure-8. Compassion between predicted and actual settlement in the raft foundation due to seismic load.

CONCLUSIONS

From results above the it can be noted that in spate of a large number of models which more than 300 models as results of variation in the input data using in modeling and analyzing the finite element package of ETABS 2015 which induce a big observation more than 2835 for the behavior of multi-story building and more than 297 observation in the behavior of the raft foundation there is a high correlations coefficient where r and r^2 are equal to 0.9 and 0.81 respectively in case of vertical settlement in the raft foundation due to gravity, wind and seismic load while r equal to 0.98 and r^2 equal to 0.95 for the story lateral displacement due to wind load finally the r and r^2 are equal to 0.84 and 0.71 respectively in case story lateral displacement due to the seismic action which acceptable results from these results it can be conclude that the modeling, analyzing by using the ETABS2015 are reliable and represent the actual facts of behavior of the multi-story building.

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