International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:5, No:3, 2011

Pushover Analysis of Short Structures

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Abstract**—**In this paper first, Two buildings have been modeled and then analyzed using nonlinear static analysis method under two different conditions in Nonlinear SAP 2000 software. In the first condition the interaction of soil adjacent to the walls of basement are ignored while in the second case this interaction have been modeled using Gap elements of nonlinear SAP2000 software. Finally, comparing the results of two models, the effects of soil-structure on period, target point displacement, internal forces, shape deformations and base shears have been studied. According to the results, this interaction has always increased the base shear of buildings, decreased the period of structure and target point displacement, and often decreased the internal forces and displacements.

Keywords**—**Seismic Rehabilitation, Soil-Structure Interaction, Short Structure, Nonlinear Static Analysis.

I. Introduction

As the people living in regions prone to having earthquakes are exposed to many detriments such as injuries, building damages, and economic losses, these damages should be considered in vulnerability and risk analysis of the area. Besides, one can mention the type of soil and the faults of the area as the earth properties of region, and enumerate the PGA, amplitude of vibrations, duration, and released energy as the properties of earthquake.

Thus by furthering our knowledge about earthquakes and the growth in concepts of retrofitting, consideration of structure's behavior in its realty have become of great importance. Consideration of factors such as effects of soil beside the structure in either viewpoint concerned to prediction and evaluation of possible damages or appreciation of soil's behavior adjacent to the structure have become of our great interest. Moreover, as there are many structures having basements, below stories adjacent to surrounding soil of structure, study of their behavior in presence of soil's stiffness in one hand and the behavior of soil on the other hand, seem to be necessary.

Generally, to consider the linear and nonlinear effects of soils on structures in Soft wares such as nonlinear SAP2000 or Perform3D, one can utilize the Link elements [1]. In the current work, the results of nonlinear static analysis of two structures without consideration of soil-structure interaction effects are compared to those of their models considering this effect using GAP elements. In addition, the maximum stress in the soil surrounding the structure is controlled by [2].

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II. Description Of Buildings And Their Loadings

The structures considered here are comprised of a three story steel skeletal structure named as S1, a four story concrete structures having skeletal system named as C1, respectively. All two structures have solid deck roofs. The plan views of these structures are shown in Fig.1.

Dead load and live load considered for all the stories of two structures According to [3]. In addition, according to [4], the effective coefficient of live load in stories of schools equals 0.4, while for the roofs of structures this coefficient equals 0.2 and the loads belonged to the walls are assigned at their exact places.

The information for type of soil have been derived from analysis results of soil mechanics laboratory, and the seismic characteristics of the site of construction are defined using the regulations of [4].

TABLE I
Specifications of structure's

Building ID	C1	S1
Cross section of columns cm	40×40	2IPE16 & 2 IPE18
Cross section of beams cm	40×40	IPE20 & IPE14
Height of basement m	3.4	3.6
Height of stories m	3.2	3.2
Height of ground above the foundation m	2.2	2.6
Soil allowed strength Kg/m^2	12400	14600

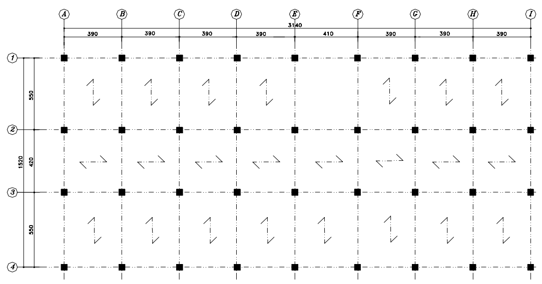

Fig. 1 (a): C1 Structure [5]

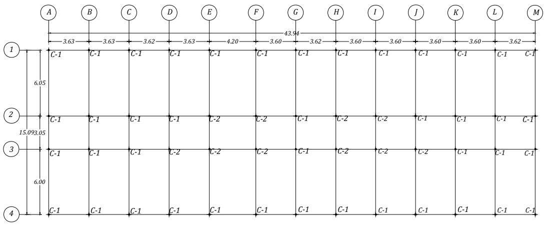

Fig. 1 (b): S1 Structure [5]

More details about these structures as well as allowable stress for their surrounding soils are presented in table 1. For S1 structure, the bracing member cross section in ground floor is UNP10, while in1st and 2nd floors are UNP8.

III. Nonlinear Static Analysis

The structures have been analyzed toward satisfaction of life safety performance. In all two structures, the load combinations are derived from [2] so that the lateral loads are assigned to the structures after the vertical loads. Besides, in the nonlinear static load case, a unified load and a load according to first mode of vibration are assigned as well. In addition, according to [2], the method of coefficients of displacement has been chosen for calculation of displacement of target point and has been adjusted according to the primary analysis based upon efficient period of structure and the control point have been observed on the roof of structure.

In extreme points of concrete beams of C1 structure, according to the ratio of longitudinal bars of cross section to balanced bars and regarding the maximum allowable interval between stirrups next to the point of conjunctions to the columns, as well as consideration of shear made in them in their first analysis, hinges have been assigned to them and modifications in further analyses regarding the variations of the shear have been made. In order to define the hinges in the columns, the tool for assignment of axial loads in SAP.Ver.12 was efficiently utilized. Besides, as in a number of columns for C1 structure, the regulations for anchorage of bars are not satisfied, especial considerations are assigned to hinges [2, 5].

In the S1 structure, the connections of columns to the foundations are hinged support. In addition, regarding the little values of moments made in the lower regions of columns, no hinges were assigned to them. Thus the columns are controlled by forces rather than moments. Moreover, as the connections of beams to the columns are of simple type, they do not participate in seismic behavior of structure, and they are only designed for gravity loads of the structure. In this structure, the force hinges are merely applied to the midpoint of bracings.

IV. Soil-Structure Interaction

A. Modeling and Criteria

The Nonlinear Gap elements are utilized in the current work to measure the allowable stress in the soil surrounding the basement and the modeling and analysis processes will be defined later [6]. In order to clarify the place of usage for Gap elements, it is worthy of notion that the basement has an opening with height of 80 cm from the bottom of ground story's floor. The Gap elements are located in connection to circumferential columns with the maximum distance of 50 cm to each other.

In order to calculate the stiffness of Gap elements connected to basement columns, the loading area of each column as well as the stiffness of adjacent soil are utilized. In other word we have:

$$K_{GAP} = \text{Area} \times k_s \tag{1}$$

Where, k_s is the stiffness of soil in kg/m^3, calculated by laboratory of soil mechanics. The analysis results in compact forces in Gap elements and the stresses in soil have been calculated, consequently. On the other hand, the loading capacity of soil considered equal to six times of allowable stress of it. In other words:

$$Q_{CE} = 3 \times 2 \times q_{all} \tag{2}$$

Where, q_{all} represents the allowable stress of soil in kg/m^3.

In order to be more realistic to the results of soil mechanic laboratory, the multiplier 2 has been entered to Eq.2.

The Gap elements are divided into two general groups: first group comprises of the elements connected to inner columns located at the circumference of the plan of basement and the second group contains those elements connected to columns located at the corners of the plan. The elements considered in the aforementioned groups are also divided into the elements completely buried in the soil and those located on the surface. The soil stiffness, k_s, stiffness of Gap elements and other details for a few elements have been presented in table.2.

TABLE II
Parameters Calculated for Gap Elements Located on the Perimeter of the Basement

Building ID	C1	S1
Number of Gap Elements	4	5
Soil Stiffness kg/m^3	1665000	1780000
Loading area for buried elements m^2	1.95×0.5	1.80×0.5
Stiffness of buried elements kg/m	1623375	1602000
Loading area for surface elements m^2	1.95×0.25	1.80×0.25
Stiffness of surface elements kg/m	811687.5	801000

Besides, for the Gaps located at the corners of the basement, the associated values presented in the table.2 should be halved.

B. Stress Control in Soil

Generally modeling the soil around the structure enables us to control the behaviour of structure and soil simultaneously, and the latter satisfies the need for experimental calculations toward control of stresses in soil. In order to calculate the stresses in soil, one can utilize the forces made in the Gap elements of the model and divide them by the loading area of the elements. This stress should be compared to the expected capacity of soil equal to six times of allowable capacity of soil [2].

The ratio of Present Stress to the Loading Capacity of Soil does not reach the unit value.

V. Interpretation Of The Results

In this section, first the analytical characteristics of the two structures have been calculated under two conditions. The first condition comprises of a nonlinear static analysis regardless of presence of soil surrounding the walls of basement, and the second condition consists of a push over analysis regarding the soil-structure interaction effects on the structure's behavior. In table.3, the period, displacement of target point and the base shear of structures are calculated under uniform loading pattern in the two aforementioned conditions and the results are compared, consequently.

TABLE III
ANALYTICAL CHARACTERISTICS OF THE STRUCTURES

Building ID	Condition 1			Condition 2		
	Tx (Sec)	δx (m)	Vx (Kg)	Tx (Sec)	δx (m)	Vx (Kg)
C1	0.617	0.064	394000	0.51	0.056	417300
S1	0.691	0.078	988200	0.614	0.068	1129000
Building ID	Condition 1			Condition 2		
	Ty (Sec)	δy (m)	Vy (Kg)	Ty (Sec)	δy (m)	Vy (Kg)
C1	0.555	0.072	362500	0.46	0.061	400650
S1	0.572	0.102	725000	0.496	0.089	895000

As it can be obviously seen, the confining effects of soil on the displacements of the structures, also affect the periods of them and this can be a cause to diminish the displacements of target points in structures. According to the Eq. (3), the displacement of target point is derived by coefficients of displacements method.

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_{eff}^2}{4\pi^2} g \tag{3}$$

In which, C_0 to C_3 are modifier coefficients, S_a is the acceleration read from the spectrum of maximum accelerations, T_{eff} is the effective period of structure and g represents the ground acceleration.

The comparison made between the final results of analysis of structures in two different conditions demonstrates that, the consideration of effects of surrounding soil on behavior of structures increases the C coefficients and reduces the periods of structures. Consequently, these variations cause an increase in base shear and a decrease in displacement of target point. Besides, it can be concluded that although the base shear of structures have been increased, because of the occurred decrease in displacement value of the target point, the number of members in which the nonlinear hinges have passed the acceptance criteria are lessened. The results for control of members in passing the acceptance criteria are presented in Table.4.

TABLE IV
NONLINEAR SAP 2000 OUTPUTS FOR ACCEPTANCE CRITERIA OF USING THE LOADING PATTERNS

C1 structure- in X-direction (%)					
Conditions	A-B	B-IO	IO-LS	LS-CP	CP-E<
1	74.7	8.4	7.9	8.9	0
2	74.7	8.4	16.3	0.5	0
S1 structure- in X-direction (%)					
Conditions	A-B	B-IO	IO-LS	LS-CP	CP-E<
1	85.8	13.8	0.3	0	0
2	87.9	12.1	0	0	0
C1 structure- in Y-direction (%)					
Conditions	A-B	B-IO	IO-LS	LS-CP	CP-E<
1	78.7	7.1	6.8	7.4	0
2	78.7	7.1	11.6	2.6	0
S1 structure- in Y-direction (%)					
Conditions	A-B	B-IO	IO-LS	LS-CP	CP-E<
1	86.2	13.1	0.7	0	0
2	88.6	11.4	0	0	0

In order to compare the types of nonlinear hinges created in the structures in the two different conditions, the percent of hinges created on structures are represented in the diagram of Figs.2 (a, b) and 2(c, d).

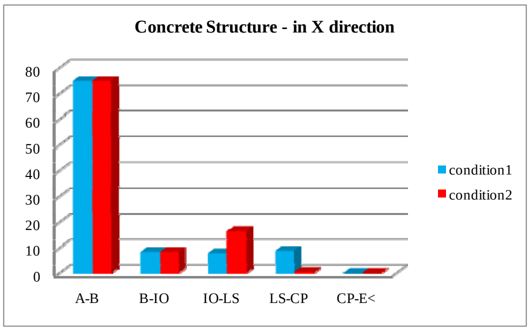

Fig. 2 (a): C1 Structure-X direction

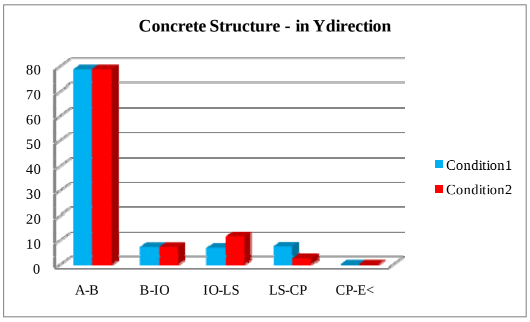

Fig. 2 (b): C1 Structure-Y direction

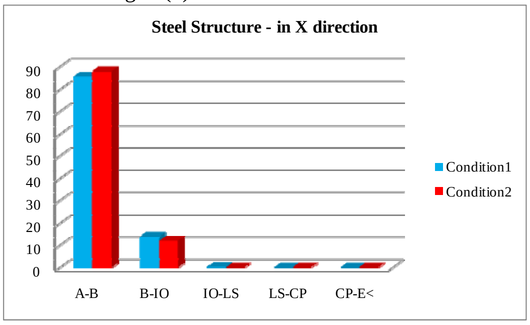

Fig. 2 (c): S1 Structure-X direction

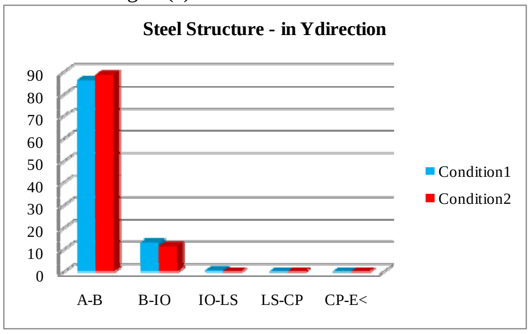

Fig. 2 (d): S1 Structure-Y direction

It is worthy of notion that although the axial forces in columns of structures, especially in S1 structure, have been increased, the final forces did not pass the acceptance criteria, therefore this increase can be treated as a more realistic behavior of structure adjacent to soil.

Finally, a comparison between the capacity curves, that is the diagram of base reaction against displacement of target point, is made for two conditions. The results demonstrate that considering the soil-structure interaction decreases the displacement of target point and increases the base shear of structure. The representations of capacity curves of two structures for two different conditions are shown in Fig3.

Although considering the soil-structure interaction increases the base shear, the efforts of structure and nonlinear hinges controlled by shape deformations will be controlled in smaller displacements and this leads to better performance in life safety performance.

As it can be observed in Fig.3 although considering the soil-structure interaction increases the base shear, the efforts of structure and nonlinear hinges controlled by shape deformations will be controlled in smaller displacements and this leads to better performance in life safety performance.

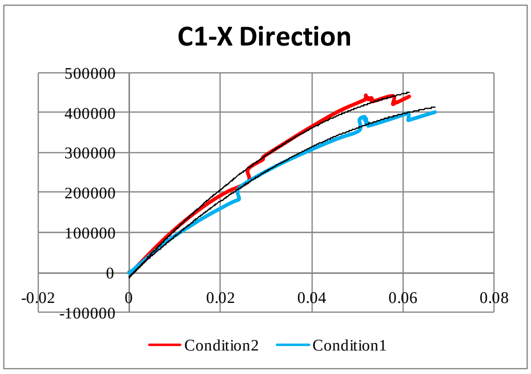

Fig. 3 (a): C1 Structure-X direction

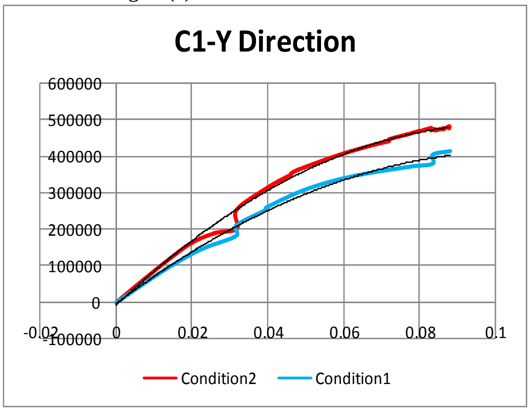

Fig. 3 (b): C1 Structure-Y direction

Fig. 3 (c): S1 Structure-X direction

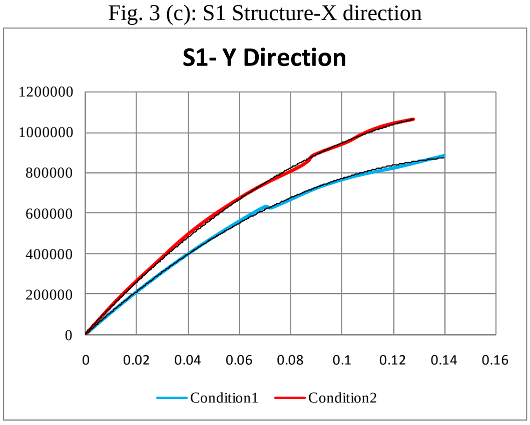

Fig. 3 (d): S1 Structure-Y direction

VI. Concluding Remark

According to necessity of seismic retrofitting of structures especially for schools and emergency centers in seismic regions in one hand, and enormous expenses of it on the other hand, consideration of factors which impact on the structural behavior of buildings and lead to more realistic models of them seems to be crucial. The effect of soil-structure interaction is one of the aforementioned definitive factors which was modeled in the current work using the Gap elements that has no stiffness in tension. Modeling the soil around the structure enables us to control the behaviour of structure and soil simultaneously; so there will be no need for experimental calculations toward control of stress in soil, consequently.

In addition, modeling the soil surrounding the basement increases the whole stiffness of structure and decreases its effective period. It also increases the coefficients of C which is utilized in calculation of displacement for target point and base shear of structure.

It can be inferred that in comparison to effects of C coefficients, the period of structure has more impact on the displacement of target point. In other words when the soil-structure interactions are considered, although the C coefficients have been increased and this causes an increase in forces made in some of members, because of the decrease occurred in the effective period of structure the displacement of target point have decreased. The aforementioned variations caused an improvement in structures' performance and aided the structure not to pass the acceptance criteria in life safety performance.

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