Computer-Aided Design of Framed Reinforced Concrete Structures Subjected to Flood Scouring

Hamed Salem

Structural Engineering Dept., Cairo University, Giza, Egypt
hamedhadhoud@yahoo.com

Abstract: In the beginning of 2010, several reinforced concrete structures collapsed due to floods in Sinai and Aswan, Egypt. Scour of soil beneath foundations lead to excessive differential settlements, failure of main structural members and finally complete structural collapse. A three-dimensional nonlinear dynamic analysis of a multi-storey reinforced concrete framed structure with induced soil scour under its foundation is carried out using the Applied Element Method. The analysis of the structure is followed until its complete collapse. The numerical analysis is then used to propose a safe design against collapse. Three different alternatives proposed for preventing progressive collapse are independently investigated; floor beams, tie beams connecting footings, and diagonal bracings. Increasing the size of the floor beams was found not to have significant effect on mitigating progressive collapse, while the use of diagonal bracings in the ground floor or rigid tie beams connecting the structure' footings was found to efficiently prevent progressive collapse. With diagonal bracings or rigid tie beams, the excessive differential settlements of the footings can be eliminated and the gravity loads can follow a safe alternative path preventing the structural collapse. The tie beam reinforcement was found to have a significant effect on the structural behavior during such an extreme loading case. Section analysis of the tie beam suggests that its ultimate strength should be based on rupture of main reinforcement, which is more economical and appropriate for such loading case.
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Key words: Flood scouring, progressive collapse, Applied Element Method, tie beams

1. Introduction

Scour occurs when floodwater passes around obstructions in the water column. As the water flows around an object, it must change direction and accelerate. Soil can be loosened and suspended by this process or by waves striking the object, and be carried away. Piles, pile caps, columns, walls, footings, and other objects found under a building can lead to localized scour. Scour effects increase with increasing flow velocity and turbulence, and with increasing soil erodibility. Excessive removal of the material around and beneath a shallow foundation can cause excessive deformation or structure collapse. As illustrated by **Richardson and Davis (1995)**, foundations for structures located in floodplains should be located below the limits of scour. If the scour depth is too deep consideration should be given to selection of a deep foundation system for support of the structure. For existing structures identified as scour susceptible, scour countermeasures are often required to protect foundations from scour conditions not identified at the time of design. Samples of scour countermeasures are the localized armoring, for example with rock or pre-cast concrete blocks, and modifications to the foundations.

Several reinforced concrete structures have been collapsed due to the floods in Sinai and Aswan, Egypt in the beginning of 2010. **Figure 1** shows snapshots of one of those collapses in Alarish city, Sinai. Flood is believed to cause huge scour for the soil beneath foundations leading to excessive differential settlements, failure of main structural members and loss of the stability of the structure. In the current study, a three-dimensional nonlinear dynamic analysis of a multi-storey reinforced concrete structure with soil scour under its foundations is carried out using the Applied Element Method (**Tagel-Din and Meguro, 2000, Meguro and Tagel-Din, 2001, Tagel-Din, 2002, Meguro and Tagel-Din, 2003, and Tagel-Din and Rahman, 2004**). The analysis is carried out to investigate the collapse behavior and the possible enhancements of the structure design so that the collapse can be prevented.

2. Research Significance

The objective of the current study is to numerically investigate the collapse behavior of multi-storey framed reinforced concrete structures subjected to soil scour beneath their foundations and to propose a design for preventing such collapse. The novelty of the current study arises from the advanced dynamic computations for the collapse analysis of reinforced concrete structures subjected to loss of soil beneath their foundations. According to the author's knowledge, this has never been carried out before. The importance of the outcome of this study arises from the need of a design/strengthening solution to the new or existing structures located in the floodplains so as to avoid their collapse during floods.

3. The Applied Element Method (AEM)

The AEM is an innovative modeling method adopting the concept of discrete cracking. In AEM, structures are modeled with elements assembly as shown in **Fig. 2**. The elements are connected together along their surfaces through a set of normal and shear springs. Those springs are responsible for transfer of normal and shear stresses among adjacent elements. Each spring represents stresses and deformations of a certain volume of the material as shown in **Fig. 2**. Each two adjacent elements can be completely separated once the springs connecting them are ruptured.

Fully nonlinear path-dependant constitutive models are adopted in the AEM as shown in **Fig. 2**. For concrete in compression, elasto-plastic and fracture model is adopted **(Maekawa and Okamura, 1983**). When concrete is subjected to tension, linear stress-strain relationship is adopted until cracking, where the stresses drop to zero. Since the method adopts discrete crack approach, the reinforcing bars are modeled as bare bars for the envelope (**Okamura and Maekawa, 1991**) while the model of **Ristic *et al.* (1986)** is used for the interior loops. The AEM is a stiffness-based method, in which an overall stiffness matrix is formulated and the equilibrium equations including each of stiffness, mass and damping matrices are nonlinearly solved for the structural deformations (displacements and rotations). The solution for equilibrium equations is an implicit one that adopts a dynamic step-by-step integration (Newmark-beta time integration procedure) (**Bathe, 1982 and Chopra, 1994**).

In the AEM, two adjacent elements can separate from each other if the matrix springs connecting them are ruptured. Elements may automatically separate, re-contact or contact other elements. **Figure 3** illustrates the different types of element contact, where contact springs are generated at contact points. In this study, the Extreme Loading for Structures (ELS) software (www.appliedscienceint.com), which is based on the AEM, is used.

The AEM was proven to be capable of following the deformations of a structure subjected to extreme loads to its total collapse (**Sasani and Sagiroglu, 2008, Sasani, 2008, Park *et al.*, 2009, and Wibowo *et al.*, 2009**. Therefore, and since the goal of the current study is to investigate the behavior of reinforced concrete structures under severe loads resulting from flood action, it was decided that the AEM is the most suitable numerical tool for such investigation. Although the Finite Element Method (FEM) is a robust and well established structural analysis method, it is not the optimum solution for the scope of progressive collapse analysis. Many drawbacks are associated with the FEM progressive collapse analysis. The elements damage, separation, falling and collision with other elements are very difficult. **Hartmann *et al.* (2008)** showed that the computations associated with the simulation of collapses of real world structures based on conventional FEM are very costly, and therefore followed another approach based on multibody models.

4. Case Studies

Figure 4, shows the geometry and the reinforcement details of the studied structure. The structure is of reinforced concrete and composed of six stories and designed for gravity loads according to the Egyptian Code of Concrete Structures, **ECCS 203-2007 (2007)**. The flooring density is assumed 1.5 kN/m^2, while the live load is assumed 3 kN/m^2. **Table 1** shows the mechanical properties of the constituent materials. The main reinforcing bars are high-grade steel, while stirrups are mild steel. The soil was assumed elastic in compression, while carrying only 0.5 MPa tensile stresses.

The effect of the flood on the studied structure was arbitrarily considered as soil scour beneath one row of columns. The soil beneath those columns was suddenly removed and the behavior of the structure was investigated. For collapse avoidance, three parameters were independently investigated; floor beams, tie beams connecting footings, and diagonal bracing. Floor beams are thought to have a contribution in activating the Vierendeel action with the columns after loss of footings' support. As shown in **Table 2**, three sizes of floor beams were studied keeping the reinforcement ratio as same as the reference case. Diagonal bracing are also thought to have a contribution in resisting footings' excessive deflections after loss of footings' support. Three different sizes of steel box diagonal bracings in the ground floor were investigated as shown in **Table 2**. It is believed that the tie beams connecting the footings could play a significant role in resisting the differential settlement and hence the potential collapse. Therefore, three different tie beams with the same geometry and with different reinforcement ratios are investigated as shown in **Table 2**.

5. Analysis Results

The behavior of the reference case is shown in **Fig. 5** where a complete collapse is observed. As clearly observed in **Fig. 5**, the tie beams could not resist the huge differential settlement resulting form soil scour. This is expected since those tie beams are not stiff enough to resist such huge differential settlement. As a result, floor beams and slabs collapsed in a progressive manner leading finally to a complete collapse.

5.1. Effect of floor beam

Figure 6 shows the effect of floor beams on the structural behavior after loss of footings' support. As seen, there is no significant effect of the expected Vierendeel action on the structural behavior, and structural progressive collapse could not be mitigated even with 1200 mm depth beams. Floor beams with depth greater than 1200 mm would not be architecturally acceptable and therefore were not considered in this study. For cases with floor beams of depths 600 mm and 800 mm, the collapse was initiated in the floor beams themselves. On the other hand, for cases with deeper floor beams, the collapse was initiated in the columns. It should, however, be mentioned that, although the increase in floor beams' dimensions did not prevent collapse, it changed the collapse pattern with reduced concrete fragments.

5.2. Effect of diagonal bracings

Figure 7 shows the effect of diagonal bracings in the ground floor on the structural behavior after loss of footings' support. As seen, the increase in the size of the bracing could efficiently lead to preventing progressive collapse for case "Br3". Despite its efficiency, the use of such bracing in the ground floor would be architecturally unacceptable, since the bracings should be installed in all bays in both directions due to the fact that the soil scour location is unpredictable.

5.3. Effect of tie beams

The structures with the relatively rigid tie beams (4S12-8, 4S12-16 and 4S12-24) did not collapse after loss of footings' support. It means that rigid tie beams may successfully resist the huge differential settlement and prevent the structural collapse. As an example for the structural behavior of the structure with rigid tie beams, **Fig. 8** shows the history of the settlement of the footings above the scoured soil case "4S12-8". As shown, the footing experienced a maximum settlement of 73 mm then reached a steady-state with a settlement fluctuating between 59 mm and 73 mm. **Figure 8** also shows the shearing forces and bending moments created in the tie beams due to those settlements, where it can be seen that the moment fluctuates between 1250 kN m and 510 kN m, while the shear fluctuates between 850 kN and 510 kN, respectively.

Figure 9 shows the deformations (ten times magnified) of the rigid tie beams connecting the footings above scoured soil. As shown, deformations get smaller with the increase in tie beam reinforcement. The ability of the tie beam reinforcement to control the settlement of the footings above the scoured soil is evident in **Fig. 10**, where the maximum settlement reduces from 73 mm to 32 mm when the tie beam reinforcement increases 3 times.

Figure 11 shows the contours of axial stresses in the tie beams for case "4S12-16", which is typical for the rigid tie beams. The critical section of the tie beam is the section with maximum bending moments and shearing forces and is located at the left boundary of the soil pit. Hysteretic stress-strain relationships for both the reinforcing bars and the concrete at points (A) and (B) along the critical section are shown in **Fig. 12**. From this figure, it can be seen that the increase in reinforcement leads to a significant decrease in both the strain and stress levels of both concrete and reinforcing bars. The increase in reinforcement from 8D18 to 24D18 caused a shift of the bar state of stress from the strain-hardening zone to the onset of yielding, where the steel stress reduced form 460 MPa to 380 MPa and the steel strain reduced from 3.4% to 0.38%, respectively. Similarly, concrete stresses and strains reduced from 30 MPa to 17MPa and from 0.25% to 0.7‰, respectively.

6. Section Analysis for Rupture Moment

As shown by the AEM analysis in **Fig. 5(b)**, the collapse of the structure is initiated due to the failure of the tie beam. The tie beam fails when its reinforcement ruptures, i.e. reaching its ultimate strain. Therefore, a section analysis that calculates the rupture bending moment for the tie beam is an essential check in the current study. At the same time, the probability of occurrence of such flood extreme loading case along the life time of the structure is relatively low and hence, it would be more economical to base the design calculations on the rupture moment rather than yield moment.

Figure 13 shows the section analysis for yield and rupture moments for tie beam in case "4S12-16" as an example. In this analysis, the yield moment is calculated at the onset of bar yielding while the rupture moment is calculated considering the bar at its ultimate (rupture) strain. The neutral axis location is assumed and the stresses in both concrete and steel are calculated using models of **Maekawa and Okamura (1983)** and **Okamura and Maekawa (1991),** respectively. The equilibrium is then checked and if it is not satisfied, the neutral axis location is reassumed until getting equilibrium of internal forces. **Figure 14** shows both yield moment and rupture moment for the three tie beams of cases 4S12-8, 4S12-16, and 4S12-24 compared to the maximum bending moments observed in those beams in the

AEM analysis. As seen in **Fig. 14**, the increase in the reinforcement of the tie beams leads to an increase in their bending moments obtained from AEM analysis. This is attributed to the fact that the increase in the tie beam reinforcement leads to an increase in its rigidity attracting more bending moments. However, the rate of increase in its rupture capacity is higher than the rate of increase in its applied bending moments leading to larger margin of safety as shown in **Fig. 14**.

Table (1) Properties of constituent materials

	Concrete	Reinforcing Bars		Structural Steel	Soil
		High-grade	Mild		
Young's modulus (MPa)	26,716	210,000	210,000	210,000	14,060
Shear modulus (MPa)	10,686	84,000	84,000	84,000	5,625
Yield stress (MPa)	---	360	240	240	---
Tensile strength (MPa)	3	540	350	350	0.5
Compressive strength (MPa)	30	540	350	350	---

Table (2) Investigated parameters

Analysis Case designation	Floor beams			Diagonal Bracing	Tie Beams		
	Section (mm x mm)	Tension RFT	Compression RFT		Section (mm x mm)	Tensio n RFT	Compression RFT
Org	250 × 600	6 D 22	3 D 22	No	300 x 600	4D16	4D16
25B80	250 × 800	8 D 22	4 D 22	No	300 x 600	4D16	4D16
25B100	250 × 1000	10 D 22	5 D 22	No	300 x 600	4D16	4D16
25B120	250 × 1200	12 D 22	6 D 22	No	300 x 600	4D16	4D16
Br1	250 × 600	6 D 22	3 D 22	HSS 4x 4x.3125	300 x 600	4D16	4D16
Br2	250 × 600	6 D 22	3 D 22	HSS 12x12x 0.5	300 x 600	4D16	4D16
Br3	250 × 600	6 D 22	3 D 22	HSS 20x20x 0.5	300 x 600	4D16	4D16
4S12-8	250 × 600	6 D 22	3 D 22	No	400x1200	8 D18	8 D18
4S12-16	250 × 600	6 D 22	3 D 22	No	400x1200	16 D18	16 D18
4S12-24	250 × 600	6 D 22	3 D 22	No	400x1200	24 D18	24 D18

Fig. 1 Collapse of a reinforced concrete house in Alarish flood, 2010

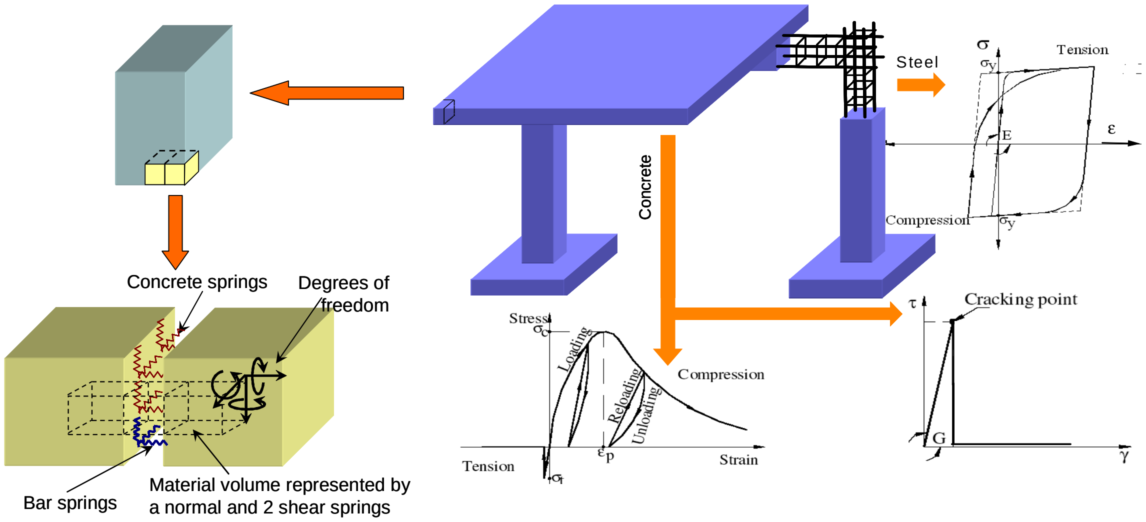
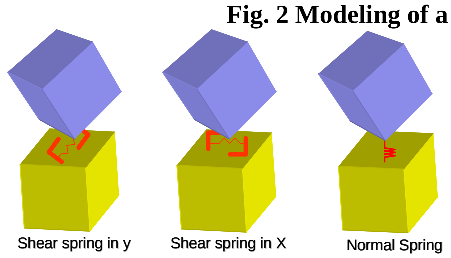
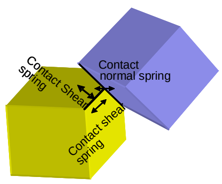


Fig. 2 Modeling of a structure with the AEM



(a) Corner-to-face or corner-to-ground contact



(b) Edge-to–edge contact

Fig. 3 Different types of elements contact

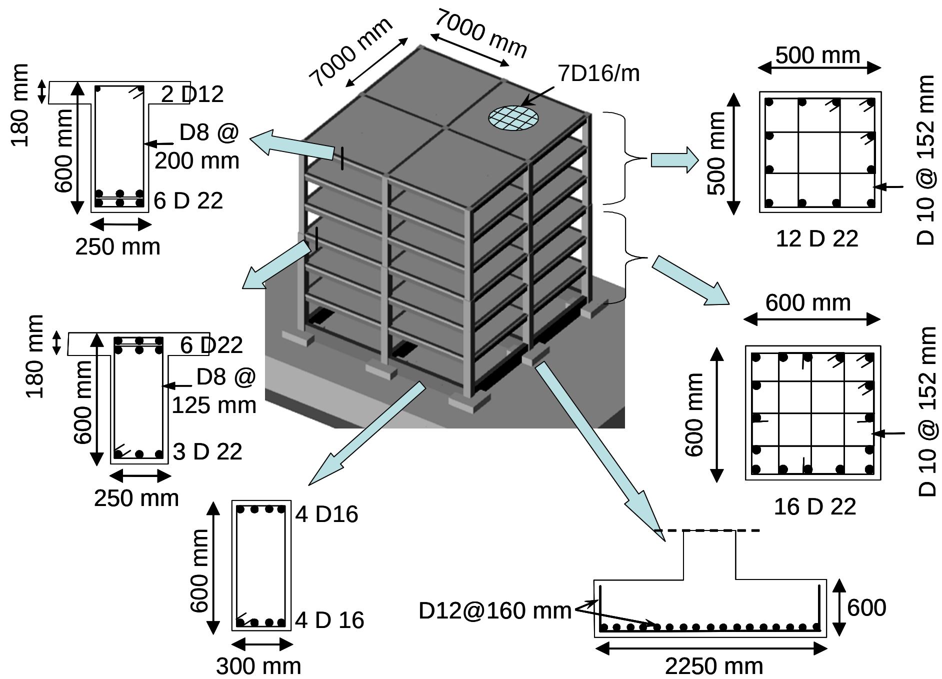
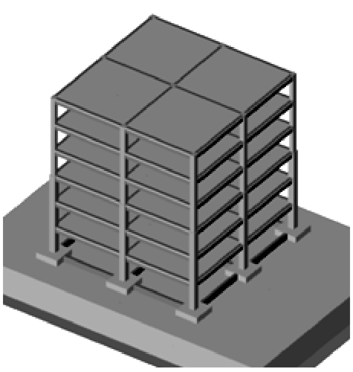
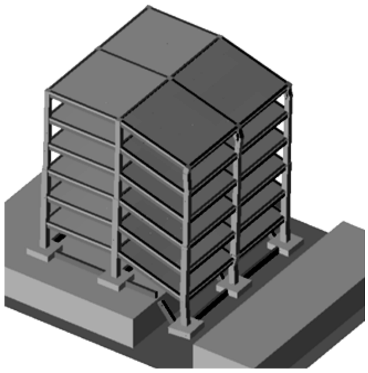
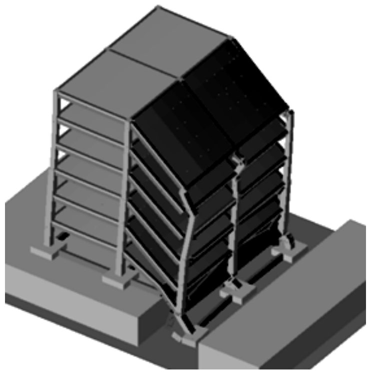
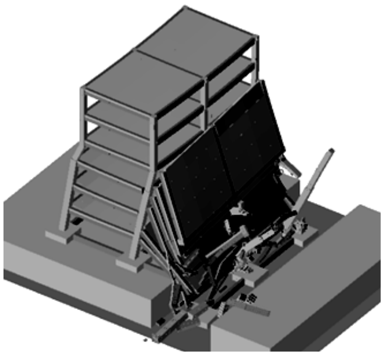


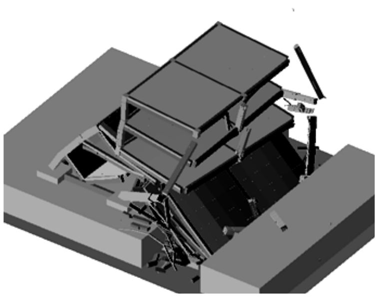
Fig. 4 Details of the multi-storey framed reinforced concrete structure


(a) Time =0.0


(b) Time= 1.0 second


(c) Time= 1.6 seconds


(d) Time= 3.0 seconds


(e) Time= 5.0 seconds

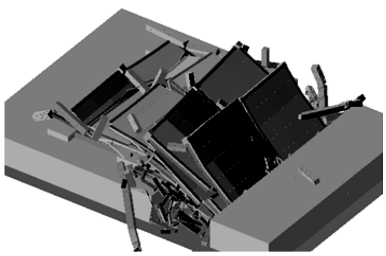
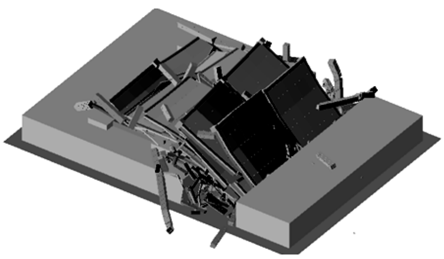
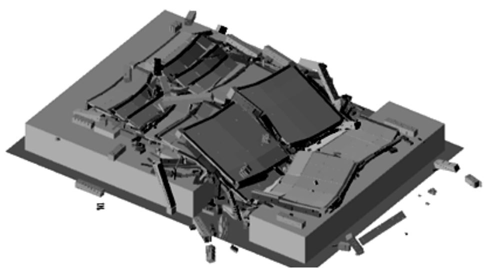
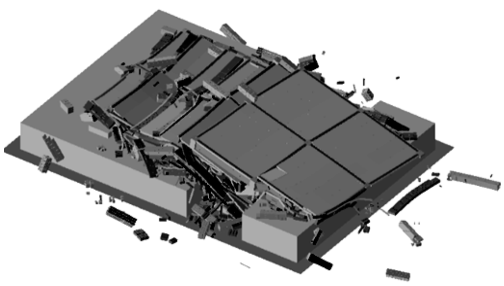

(f) Time= 6.0 seconds

Fig. 5 Numerically-obtained progressive collapse for reference case (Org)


(a) Case (Org)


(b) Case (25B80)


(c) Case (25B100)

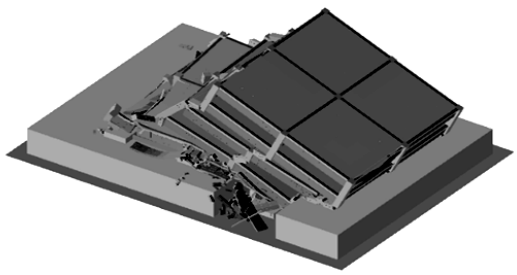
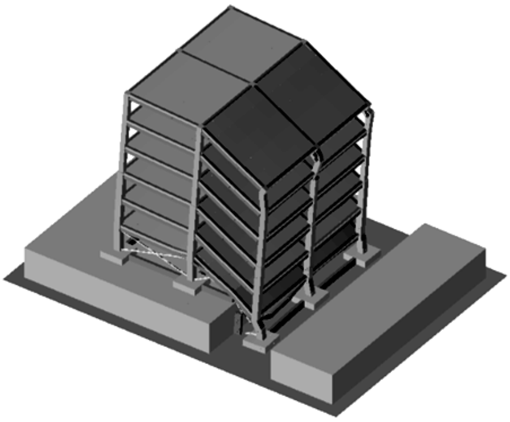
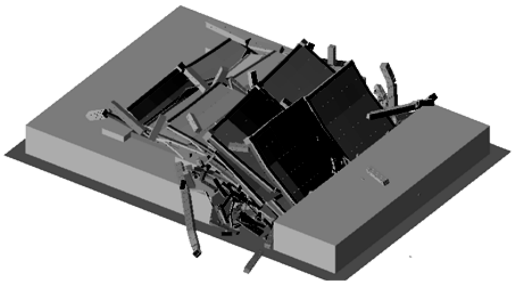

(d) Case (25B120)

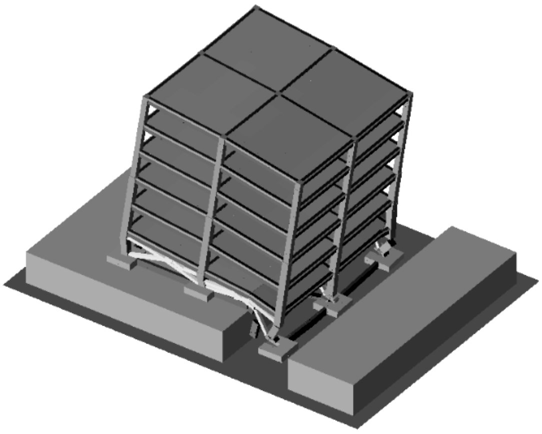
Fig. 6 Effect of floor beam on collapse avoidance

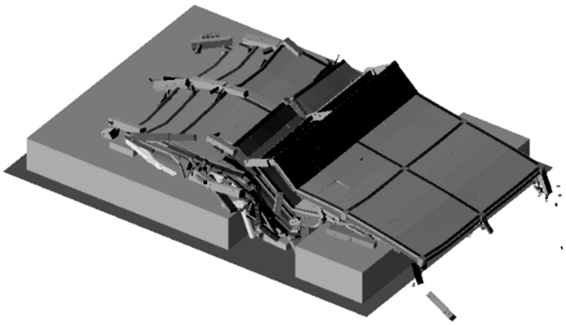




a-1) Time= 1.0 second **a-2) Time= 6.0 seconds**

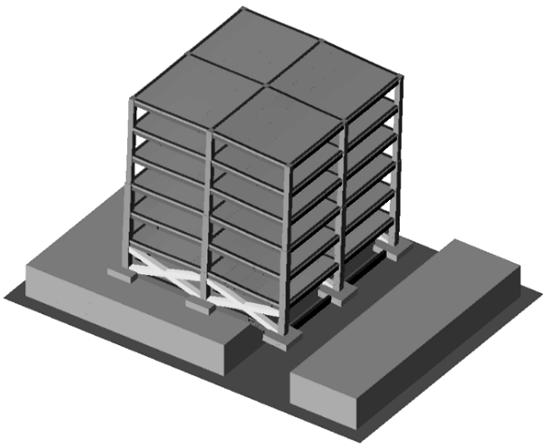
(a) Case (Br1)

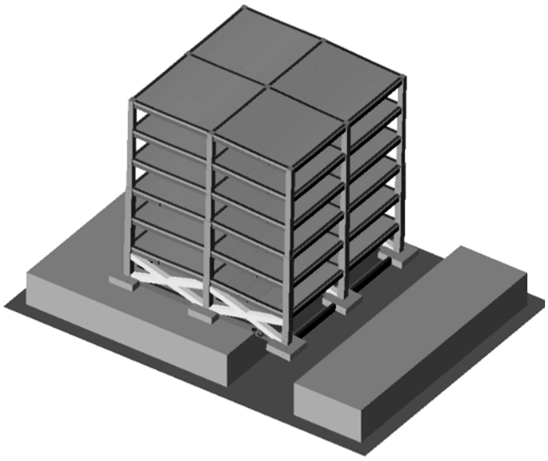




b-1) Time= 1.0 second **b-2) Time= 6.0 seconds**

(b) Case (Br2)





c-1) Time= 1.0 second (deformations x 10) **c-2) Time= 6.0 seconds (deformations x 10)**

(c) Case (Br3)

Fig. 7 Effect of diagonal bracing on collapse avoidance

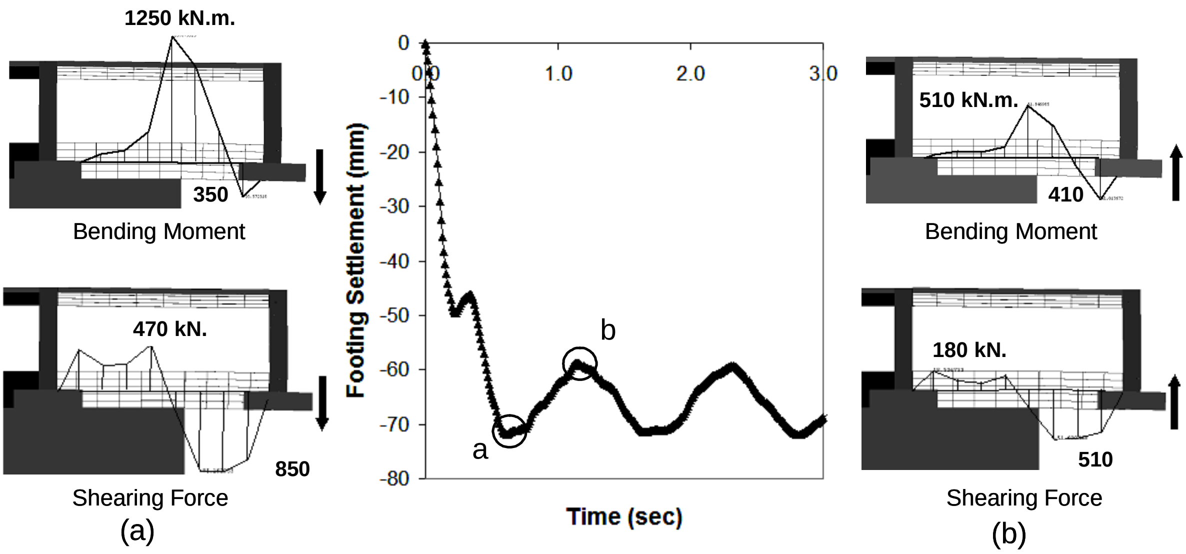
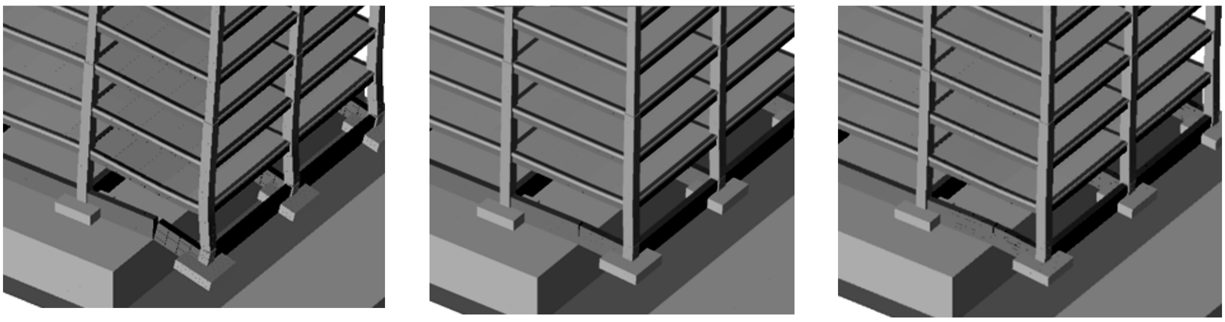


Fig. 8 Settlement history of the footings and corresponding straining actions in tie beams for case (4S12-8)



(a) 4S12-8 (b) 4S12-16 (c) 4S12-24

Fig. 9 Structural deformation (ten times magnified) for the structures with rigid tie beams

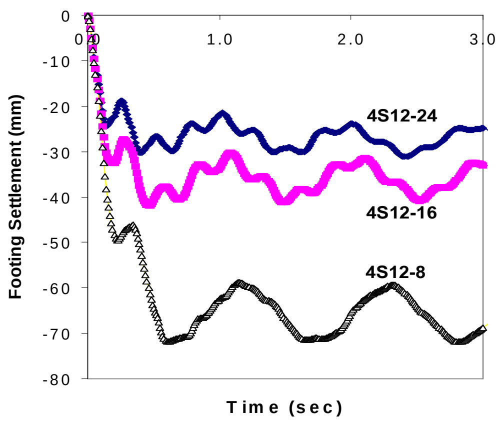


Fig. 10 Settlement history of the footings for structures with rigid tie beams

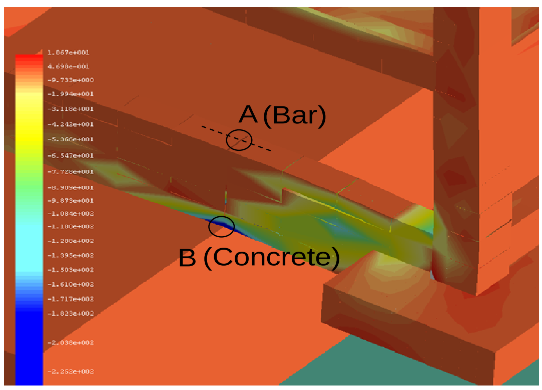
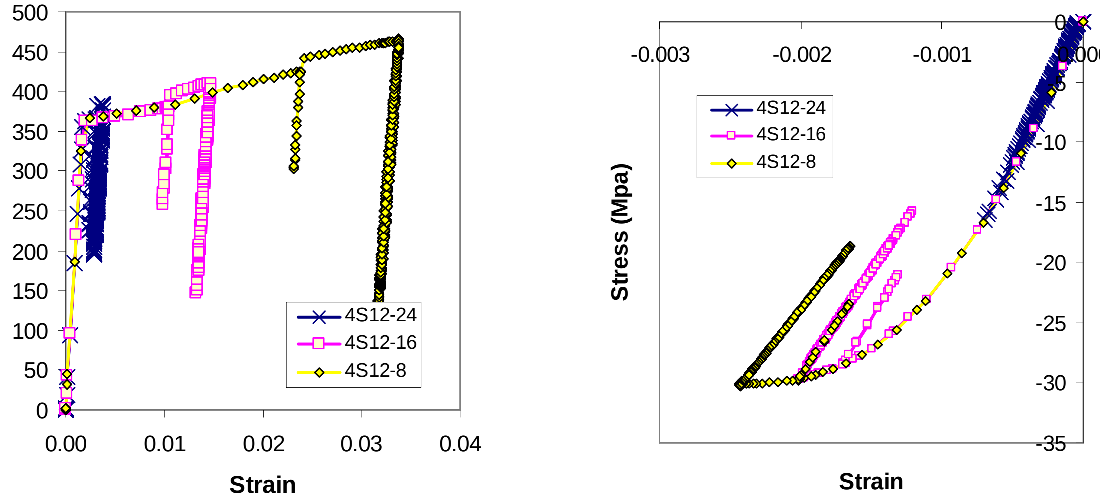


Fig. 11 Axial stress contours in the tie beam of case(4S12-16)



(a) Reinforcing bars (point A) **(b) Concrete (point B)**

Fig. 12 Stress-strain for rebars and concrete at points (A) and (B) in rigid tie beams

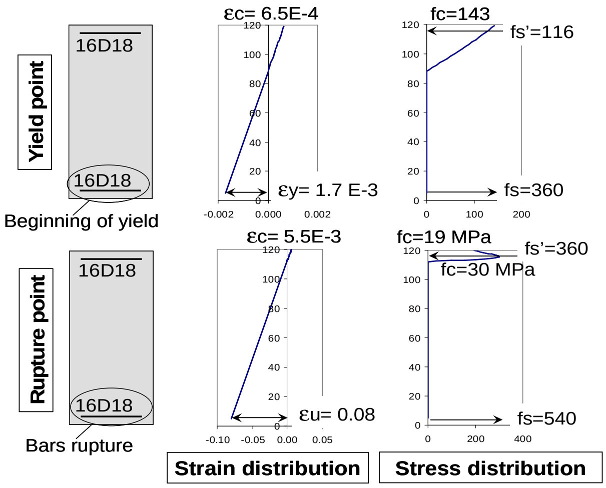


Fig. 13 Section analysis for yield and rupture points

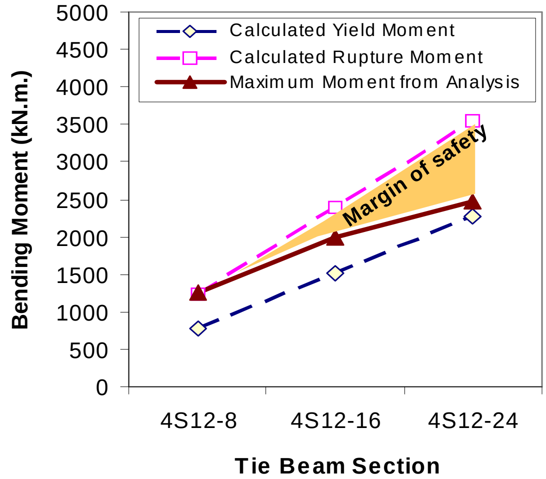


Fig. 14 Effect of reinforcement ratio on the capacity of tie beams

Conclusions

A three-dimensional nonlinear dynamic analysis of a multi-storey reinforced concrete framed structure with induced soil scour under its foundation is carried out using the Applied Element Method (AEM). The analysis of the structure is followed until its complete collapse. Three different alternatives proposed for preventing progressive collapse are independently investigated; floor beams, tie beams connecting footings, and diagonal bracing. The main conclusions can be summarized as follows;

- The loss of footing support due to soil scour lead to a progressive collapse of the studied framed structure.
- Increasing the size of the floor beams, within the acceptable architectural range, was found not to have significant effect on the structural behavior. The activated beam-column vierndeel action can not mitigate structural progressive collapse.
- The use of diagonal bracings in the ground floor was found to efficiently prevent progressive collapse. Diagonal bracings help gravity loads to

follow a safe alternative path preventing the structural collapse. Despite its efficiency, the use of such bracings would be architecturally unacceptable because they should be installed in all bays in both directions due to the fact that the soil scour location is unpredictable.

- Rigid tie beams connecting the columns footings help preventing the excessive differential settlements of the footings and prevent structural progressive collapse. The tie beam reinforcement was found to have a significant effect on the behavior of the structure during such extreme loading case. The increase in the reinforcement ratio significantly reduces the differential settlement and reduces the level of stress in both concrete and reinforcement.
- Section analysis of the tie beam suggests that its ultimate strength should be based on rupture of main reinforcement, which is more appropriate and economical for such extreme loading case.

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Corresponding author
Hamed Salem
Structural Engineering Dept., Cairo University, Giza, Egypt
hamedhadhoud@yahoo.com

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