Efficient seismic analysis of high-rise buildings considering the basements

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ABSTRACT: Many high-rise buildings are designed with basement. In general, we assume that a building is fixed at the ground level. Therefore, the basement of the building is not included in the analysis and only gravity loads are considered in designing the basement. However, the basement may introduce flexibility to the structure resulting in larger lateral displacements and longer vibration periods. The seismic loads applied to a building structure will affect the member forces in the basement. Thus, it is recommended to include the basement in the analysis of high-rise building structures. The effect of the basement is investigated based on the seismic response of high-rise buildings and an efficient analysis method to account for the effect of the basement was proposed in this study. Most of the degrees of freedom in the basement are eliminated by the matrix condensation procedure using a rigid diaphragm for each floor in the basement in part or in full. When a 20-story building structure was subjected to static lateral loads, the displacements of the roof were 13.8cm and 12.7cm for the cases with and without the basement. And the period of the building with the basement was about 10% longer than that of the building without the basement. Therefore, it is recommended to use the proposed method to get more accurate results in the analysis of building structures with basement.

1 INTRODUCTION

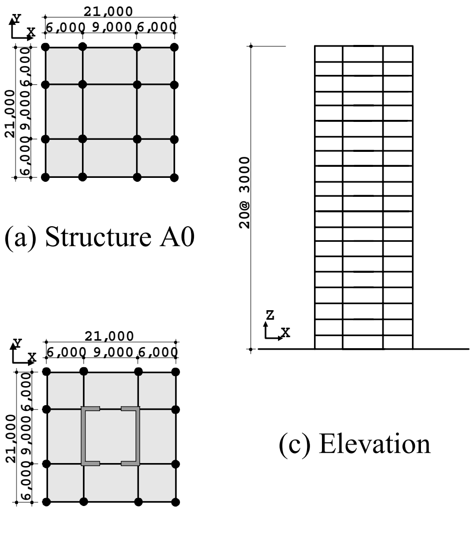
Recently, most of the high-rise buildings may have basement used as parking lots or shopping malls etc. In general, it is commonly assumed that the building is fixed at the ground level in the analysis and the basement is not included in the analytical model. Using this assumption, the lateral stiffness of the structure may be overestimated since the flexibility introduced by the basement is ignored. Therefore, the natural periods may be shortened and the dynamic response of a building structure may be misestimated due to this inaccurate prediction of the lateral stiffness.

In general, only gravity loads are considered in designing the basement structure without the effect of lateral forces as earthquake loads applied to the super structure such. But the seismic loads applied to the super structure will affect the member forces in the basement structure. The previous researches on buildings with basement were only focused on the dynamic behavior of a structure using a simplified model and could not cover the effect of seismic loads on basement structural members. The effect of the basement on the seismic response of high-rise buildings and the effect of the seismic loads on the member force of the basement were investigated in this study. Especially in seismic analysis of high-rise building structures with basement, it is of practical importance to obtain an accurate estimation of the high shear force acting on the basement structure. Therefore the shear force in the basement is carefully investigated in this study. And an efficient method is proposed for the analysis of high-rise buildings considering the effects of basement by using partial or full rigid diaphragm and matrix condensation procedure.

2 EFFECT OF BASEMENT ON SEISMIC RESPONSE OF HIGH-RISE BUILDINGS

2.1 *Example structures*

A typical framed structure (structure type A) and a framed structure with a reinforced concrete core (structure type B) were used as example structures to investigate the seismic response of high-rise buildings with basement. The structure type A was modeled as the structure A0 which is fixed on the ground level as shown in Fig.1 and the structure A5 which has five stories in the basement as shown in Fig.2. The structures A1, A2, A3 and A4 have 1, 2, 3 and 4 stories in the basement, respectively. Similarly, the structure type B was also modeled as B0, B1, B2, B3, B4 and B5 as shown in Figs. 1 and 2 according to the number of stories in the basement. All example structures have 20 stories above ground and the structural behavior was investigated by varying the number of stories in the basement from 1 to 5. Equivalent static analysis, eigenvalue analysis, response spectrum analysis and time history analysis were performed on all of the example structures.

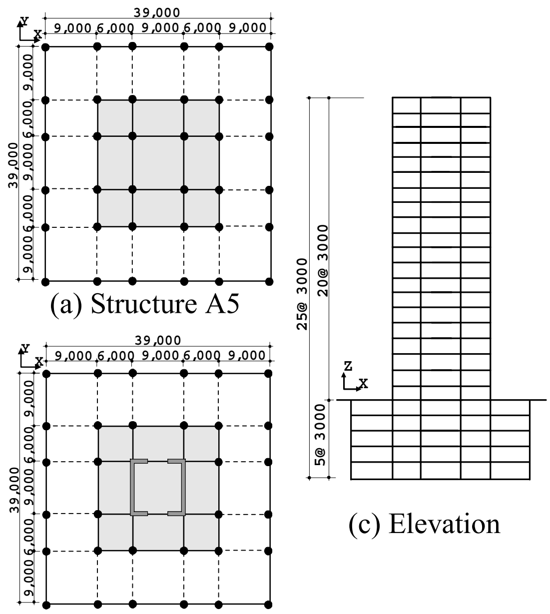


(a) Structure A0

(b) Structure B0

(c) Elevation

Fig 1. Example structures w/o basement



(a) Structure A5

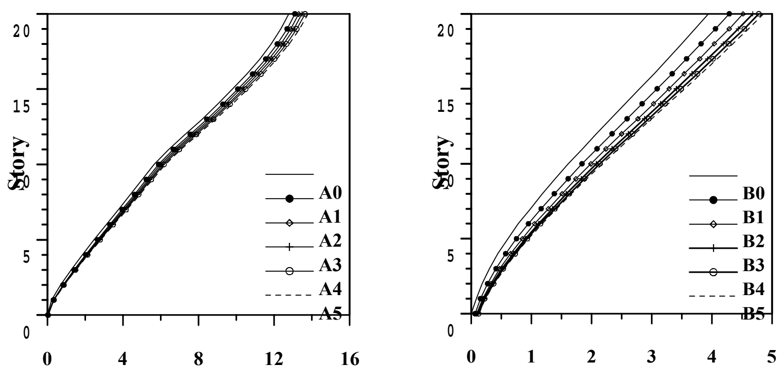
(b) Structure B5

(c) Elevation

Fig 2. Example structures w/ basement

2.2 *Lateral displacements*

The lateral displacements from the equivalent static analysis are shown in Fig 3. As the number of stories in the basement increases, the rotation at the bottom of columns in the first story increases because of the flexibility introduced by the basement structure. Due to this phenomenon, the lateral stiffness decreases resulting in the increase of the lateral displacements. Especially in the case of the framed structure with a core, this tendency was more significant.

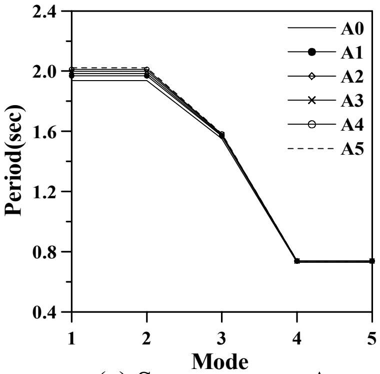


(a) Structure type A (b) Structure type B

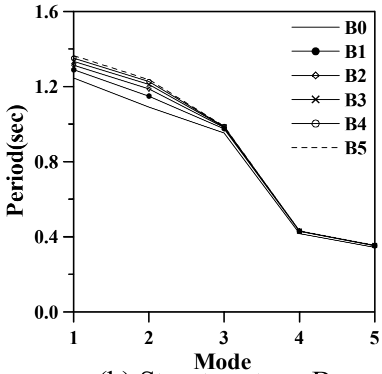
Fig 3. Comparison of lateral displacements

2.3 *Natural periods of vibration*

Natural periods of vibration for the example structures were compared in Fig 4 that illustrates that natural periods of the structure types A and B become longer as the number of stories in the basement were increased. And the difference in the natural period for the lower modes was more significant compared to that of the higher modes. It can be explained that the rotation of column bases occurring in the first and the second mode shapes is larger than that of the higher modes.



(a) Structure type A



(b) Structure type B

Fig 4. The effects of the basement on the natural periods

2.4 *Response spectrum analysis results*

The difference in the natural periods will result in the difference in the seismic response. In general, the natural periods of a structure considering the effects of the basement are longer than that of the structure without basement structure. The accelerations of the structure with a basement tend to be smaller, because the natural periods of the structure types A5 and B5 are longer than those of the structures A0 and B0, respectively. Therefore, if the basement structure is included in the analytical model, the seismic loads in the response spectrum analysis become relatively small. Even though the difference in the periods is small, the difference in the spectral acceleration becomes larger when the period is relatively short because the slope of the response spectrum becomes steeper. The base shear forces of the example structures from the response spectrum analysis are listed in Table 1.

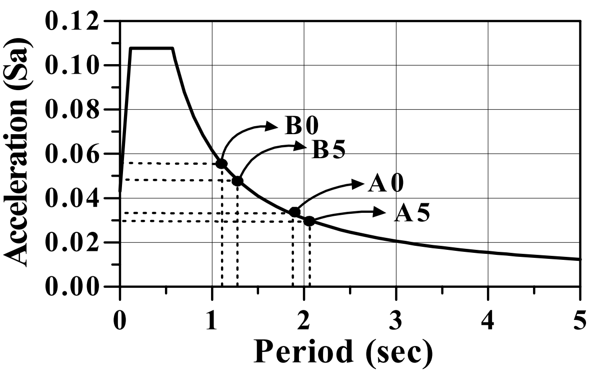


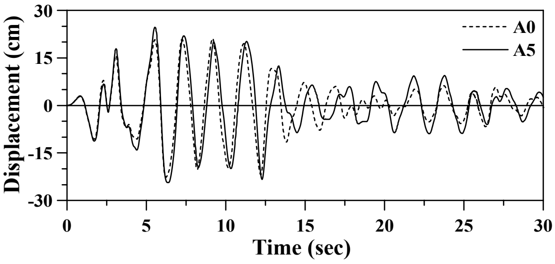
Fig 5. Difference of acceleration caused by basements

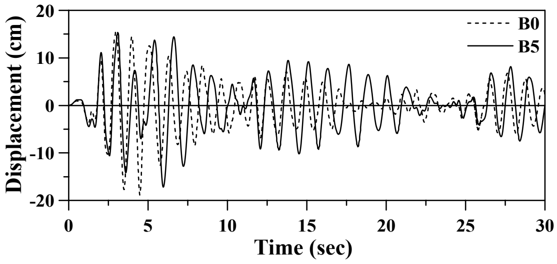
Table 1 Base shear from the response spectrum analysis (unit : tonf)

Number of stories in basement	Structure type A	Structure type B
0	320.5	281.1
1	320.4	279.2
2	318.3	274.1
3	316.5	270.6
4	314.8	268.4
5	313.6	266.7

2.5 *Time history analysis results*

The roof displacement time histories obtained using the N-S component of the El Centro earthquake(1940) as the input ground motion for the time history analysis of the structure types A and B are compared in Fig. 6. The difference in the displacement time histories of the structure type A was less significant than that of the structure type B as illustrated in Fig. 6 as could be expected from the differences in the natural periods of vibration of both structures.





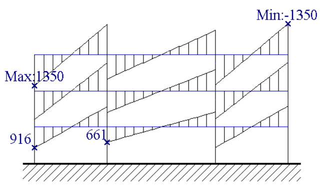
(a) Structure type A (b) Structure type B

Fig 6. Displacement time history at roof

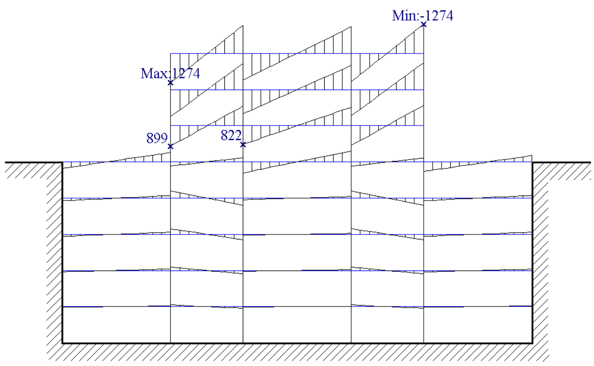
3 EFFECT OF LATERAL FORCES ON MEMBER FORCES OF BASEMENT

3.1 *Bending Moments of Members in the Basement*

When designing the basement structures, it is assumed that the seismic loads do not affect the basement structure and only gravity loads are considered in the analysis while the member forces in the basement structure may be significant. The bending moments in the first three stories and the basement of the example structures from the equivalent static analysis are illustrated in Figs.7, 8, 9 and 10. The bending moment diagrams for the beams and columns of the structures A0 and A5 are shown in Figs. 7 and 8. The bending moments in the lower stories of the structure A5 are smaller than those of the structure A0 because the bending moments are redistributed to the basement structure. In the case of the structure A5, the bending moments in the columns were significant in the first basement.

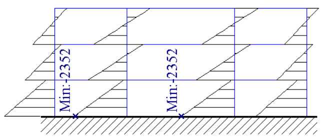


(a) Structure A0

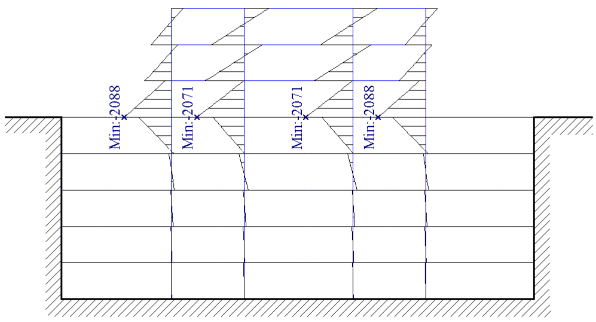


(b) Structure A5

Fig 7. Bending moment of beam in structure A



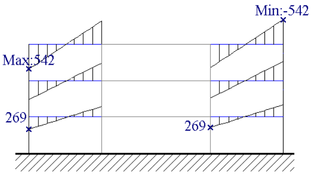
(a) Structure A0



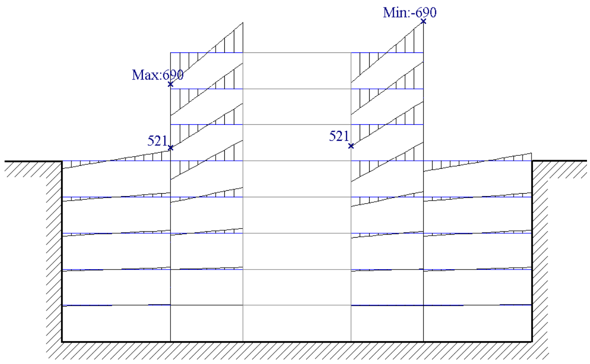
(b) Structure A5

Fig 8. Bending moment of column in structure A

On the contrary, the existence of the basement resulted in larger bending moments in the lower stories of the structure type B as illustrated in the bending moment diagrams for the beams and columns shown in Figs. 7 and 8. Especially in the first floor, the bending moments of the structure B5 were noticed to be about twice of that of the structure B0. And the bending moments of basement structures are significant, too. Therefore, in the case of a framed structure with a core, the basements should be considered in the seismic analysis for conservative design.

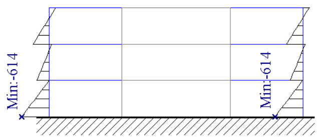


(a) Structure B0

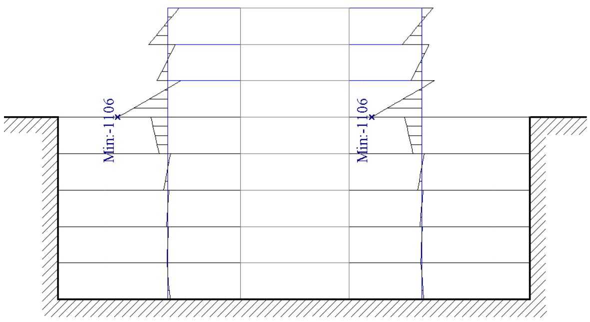


(b) Structure B5

Fig 9. Bending moment of beam in structure B



(a) Structure B0

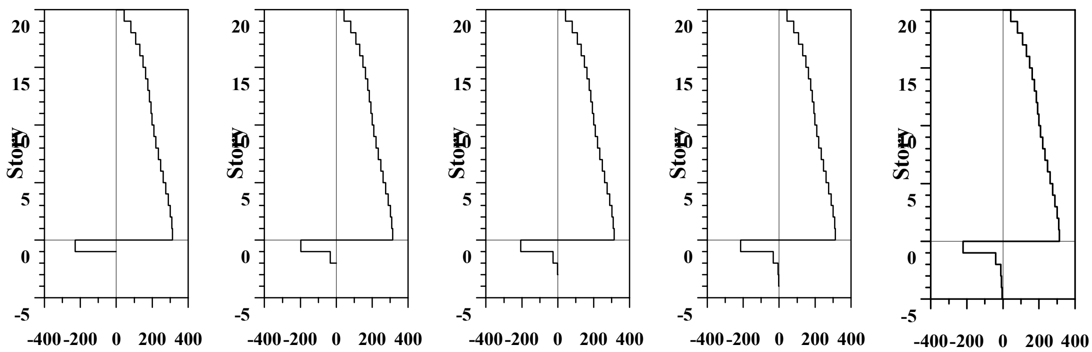


(b) Structure B5

Fig 10. Bending moment of column in structure B

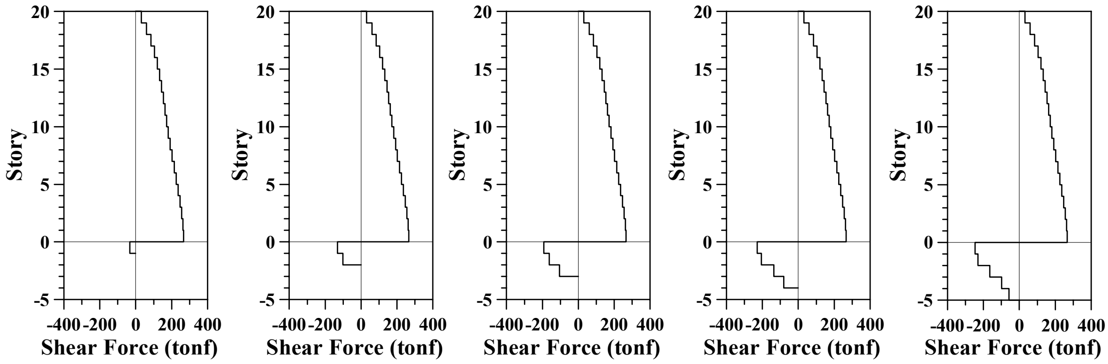
3.2 *Shear Forces in Basement*

The story shear force distributions from the equivalent static analyses of the structure types A and B are shown in Figs. 11 and 12. The shear force in the first basement is much larger than those in the other basements of the structure type A as illustrated in Fig. 11. On the contrary, the shear force is the largest in the first basement and it is gradually reduced in the lower basements of the structure type B as could be noticed in Fig. 12



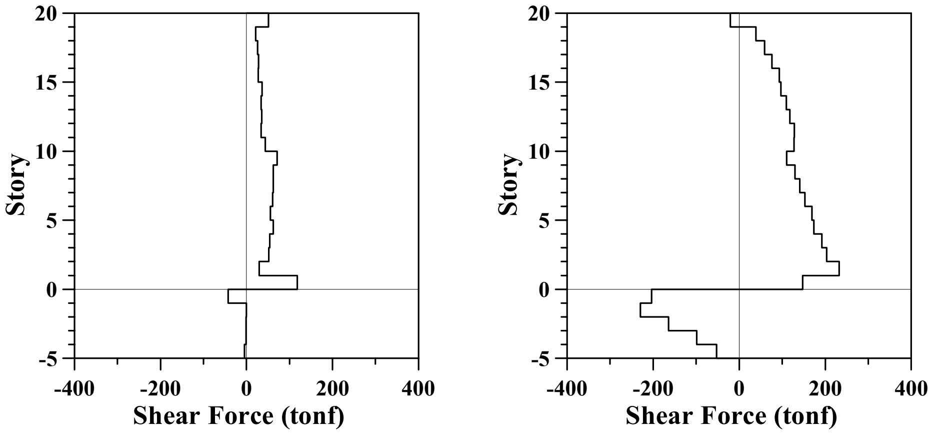
(a) Structure A1 (b) Structure A2 (c) Structure A3 (d) Structure A4 (e) Structure A5

Fig 11. Story shear force distribution in the structure type A



(a) Structure B1 (b) Structure B2 (c) Structure B3 (d) Structure B4 (e) Structure B5

Fig 12. Story shear force distribution in the structure type B



(a) frame (b) core

Fig 13. Shear force of structure B5

The portions of story shear force in the frame and the core of the structure B5 are shown in Figs. 13(a) and 13(b). The portion of story shear force in the core is much larger in all of the stories except at the top of the structure. The large shear forces of the frame in the first floor and the first basement noticed in Fig 13(a) was leading to large bending moments in the columns as shown in Fig. 10(b).

4 EFFICIENT SEISMIC ANALYSIS OF HIGH-RISE BUILDING STRUCTURES WITH BASEMENT

4.1 *Rigid Diaphragm Assumption and Matrix Condensation*

In the analysis of high-rise building structures, the stick model which has 3 in-plane DOF`s per floor is usually used in commercial software, such as ETABS, by applying the rigid diaphragm assumption and the matrix condensation technique. But if the rigid diaphragm assumption is applied to the basement structure, the story shear forces in the basement may be significantly overestimated since the flexibility of the floor systems in the basement is ignored. The analytical model which does not use the rigid diaphragm assumption and the matrix condensation is identified as the model ND in Fig. 14 and it is expected to provide the most accurate result in static or dynamic analyses. The models FD and PD employ the matrix condensation technique and assume each floor system as a rigid diaphragm identified by the shaded area. The model FD assumes each floor system as a rigid diaphragm while the model PD utilize partial rigid diaphragms limited to the floor slabs in the basement corresponding to the floors in the super structure as shown in Fig. 14.

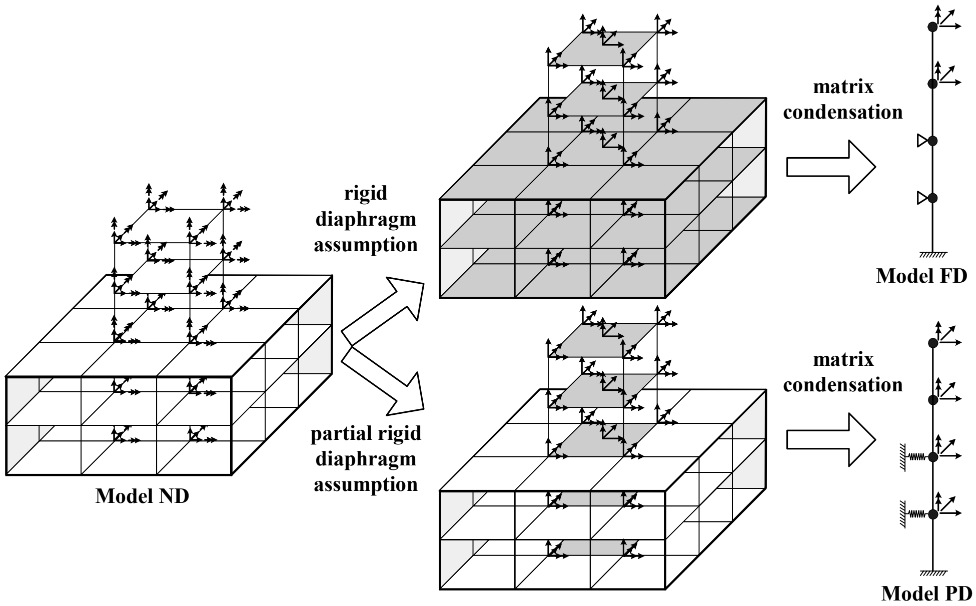
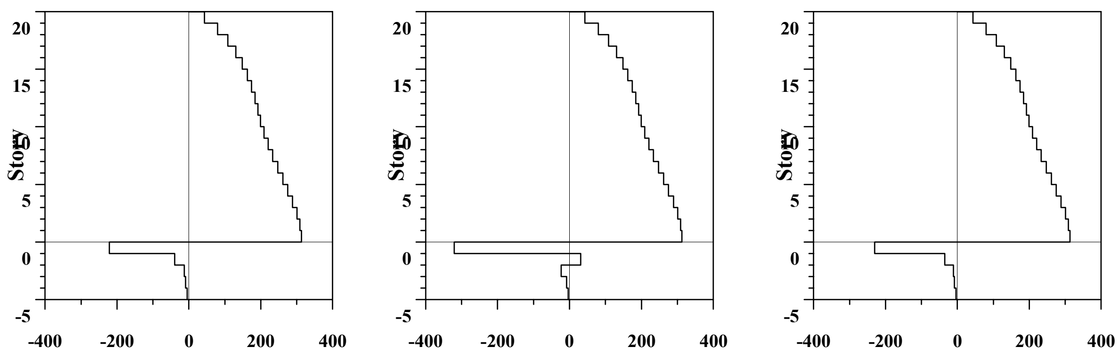


Fig 14. Reduction of DOF`s by rigid diaphragm assumption and matrix condensation

4.2 *Comparison of the shear forces in the basement*

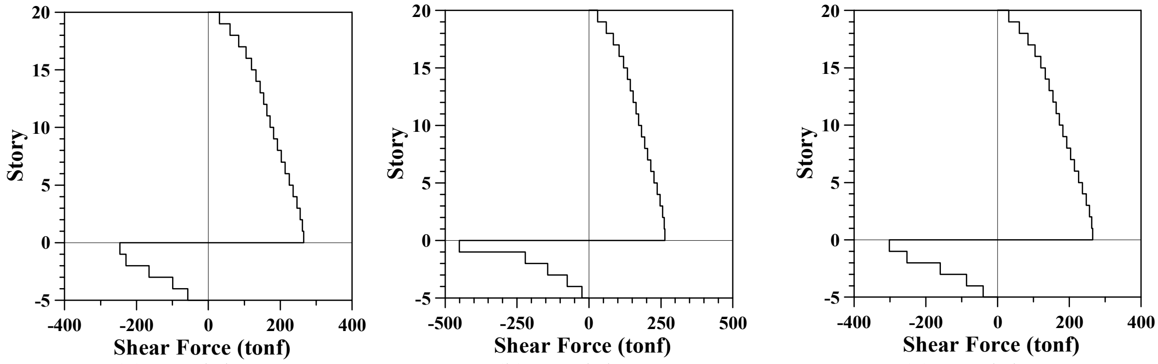
Equivalent static analyses of structures A5 and B5 were performed using three different models shown in Fig. 14 to investigate the effect of the rigid diaphragm assumption on the prediction of the seismic response of multistory structures with basement. Seismic response of high-rise building structures with basement may be significantly different from those of the structures without basement. Thus, seismic response of high-rise building structures in the basement can be predicted by including the basement in the analytical model. An accurate prediction of the shear force in the basement is very important in the seismic analysis of high-rise building structures with basement. Therefore, story shear forces of models FD and PD were compared to those of the model ND which is expected to be the most accurate. In the case of the structure A5, the story shear force in the first basement was overestimated about 50% and the sign of story shear force in the second basement was changed in the model FD as shown in Fig. 15 while the shear force of the model PD was very close to that of the model ND.

In the case of the structure B5, the story shear forces in the basement of the model FD were significantly overestimated compared to those of the model ND as illustrated in Fig. 16. while the model PD resulted in the shear forces with minor overestimation compared to those of the model ND. Therefore, the model PD is proposed for analysis of multistory building structures with basement to account for the effect of the basement on the seismic response.



(a) Model ND (b) Model FD (c) Model PD

Fig 15. Shear force distribution in the basement of the structure A5



(a) Model ND (b) Model FD (c) Model PD

Fig 16. Shear force distribution in the basement of the structure B5

5 CONCLUSIONS

The effect of the basement on the seismic response of high-rise buildings and the effect of the lateral forces applied to the superstructure on the member forces in the basement were investigated in this study and the following conclusions could be drawn.

1. Lateral stiffness of a high-rise building structure may be significantly overestimated resulting in larger lateral displacements and shorter natural periods of vibration if the basement of a high-rise building is ignored in the analytical model. Especially in the case of the building structures with shear walls, the effect of the basement on the seismic response turned out to be more significant. Therefore, it is necessary to include the effect of basement in the analysis of high-rise building structures.

2. Lateral loads affect not only the response of the super structure but also that of the basement structure. Therefore, seismic loads as well as gravity loads should be considered in the analysis of a high-rise building structure for the design of the basement structure.

3. The story shear forces in the basement may be significantly overestimated if the rigid diaphragm assumption is applied to the basement. Therefore, an efficient analysis method using partial rigid diaphragms is proposed in this study for the analysis of high-rise buildings subjected to lateral forces such as the seismic loads including the effects of basement.

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