ATLANTIS PRESS

Advances in Engineering Research, volume 199

Proceedings of the 4th International Conference on Sustainable Innovation 2020–Technology, Engineering and Agriculture (ICoSITEA 2020)

The Influence of Subsidence Angle to Column Demand-Capacity Diagram of a Multistory Building

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ABSTRACT

Earthquake is an unpredictable natural disaster, and land subsidence is one of the followed impacts of this disaster. This occurrence can endanger buildings on the disaster area, especially the columns as the central element in the superstructure. This study aims to discover the influence of the inclination angle resulting from the settlement to the axial-moment interaction ratio of the column in a multistory building. The object of this research was Building E functioning for educational purposes and located in the Special Region of Yogyakarta (DIY), Indonesia, with sandy soil conditions. The numerical analysis was simulated by applying the displacement in all supporting systems linearly corresponding to one side-end of a building. Six typical column types in Building E were sampled for investigation, and six variations of inclined subsidence were simulated. Earthquake response spectrum was loaded in all variations of subsidence angle and simulated. The analysis results revealed that several types of columns in Building E was unable to withstand the force after suffering a slope of 0.04°. At the largest simulated angle, 0.1°, only the interior column around the building could be categorized as safe, while several other column types close to the outer perimeter of the building were in critical condition, and some have exceeded their capacity.

Keywords— Reinforced concrete, column, interaction diagram, axial-moment, settlement

1. INTRODUCTION

Earthquake is an unavoidable natural disaster. Even multistory reinforced buildings may collapse due to this ground motion, and the condition is aggravated if followed by liquefaction events, which commonly occur in sandy soil. Liquefaction is a phenomenon involving the decay of shear resistance and excessive deformation caused by monotonic or repeated loading of saturated soils [1]. The liquefaction will significantly influence the strength of the foundation of structures. Once the foundation faces a problem, the superstructure is undoubtedly affected, especially the column as the main element for transferring all forces to the supporting system. Several studies have revealed the causes behind the liquefaction, including the total subsidence and the resulted angle corresponding to the horizontal line. Liquefaction can be influenced by seismic vibrations, whereas damage or collapse of buildings can be caused by both [2]. Several liquefaction causes include the uncertainty of soil movement and the nature of existing land. Subsidence may occur uniformly or only on one side of the building while the other side is relatively fixed, thus forming an angle (see Fig. 1). The symbol Δ_v represents the magnitude of the subsidence [3]. Liquefaction occurs due to a sudden increase of pore pressure in the hollowed layer that does not undergo compression, causing a loss of strong support or capacity [4].

Several studies have been conducted to determine the causes, the decline magnitude, and the tilt magnitude occurring due to liquefaction. Research on liquefaction in Indonesia has been carried out by taking objects in areas with high seismicity, Yogyakarta, more precisely at Universitas Muhammadiyah Yogyakarta (UMY), standing on sandy soil. The study disclosed that the acceleration caused by the ground motions in the UMY area resulted in land subsidence of 1% [5]. The earthquake hitting the Yogyakarta area caused a lot of damage in the UMY environment, and some damage occurred due to liquefaction causing land subsidence ranging from 2.5 to 13.5 cm [6]. The structural geometry influenced the tilt of the building, its direction, and the foundation used. Besides, the structural self-weight and soil conditions were also factors causing different damage levels to buildings [7]. Lu et al. has investigated the impact of liquefaction on low-rise building in the Meinong Earthquake (2015), Taiwan [8], suggesting that the local site effects are essential to be considered. Otherwise, the damage severity is inconsistent. The most considerable damage found was the tilted building about 3° to the west and 4° to the south with subsidence about 90 cm. Ashford et al. reported environmental damage due to the Tohoku earthquake's liquefaction in 2011 [9]. Some low-rise buildings were reported to have settled and tilted, leading to the utility damage. Moreover, a wind turbine was detected to have a tilt of 1.6°. Besides, several studies have examined the performance of the reinforced concrete multistory building under earthquake loads [10-12] and even for the sloping ground [13].

Inclined subsidence triggers the buildings to tilt and enlarge the moment forces acting on the structural columns. Furthermore, it will raise the risk of building collapse due to the seismic activity. Even though many researchers have

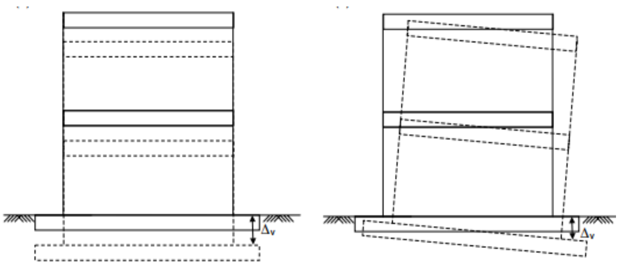


Fig. 1. Subsidence on building [1]

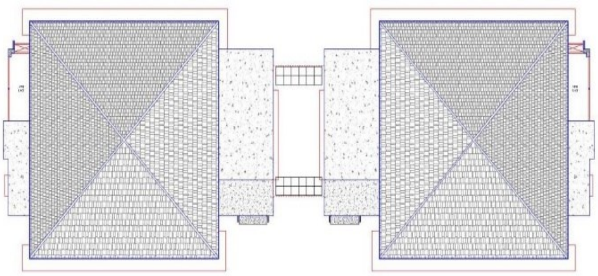
investigated the causes of building subsidence and the building response against the earthquake, they paid significantly less concern to the column demand-capacity on the tilted building. A special examination must be performed to study the effect on the main superstructure element of the building. Therefore, this study aims to investigate the demand-capacity of tilted building columns to withstand the above problem. The analysis was performed by examining the influences of subsidence on the axial-moment column capacity by varying the subsidence angle.

2. RESEARCH FRAMEWORK

The study began with data collection, followed by the load calculations, such as the gravity loads and lateral force. According to the Indonesian seismic code, the response spectrum was applied in this numerical simulation with the shear force controlled by the equivalent lateral force (ELF). Roofs and wall elements of the building were computed separately and loaded their reaction to the 3D numerical model. Thereby, the open frame structure was established. The linear analysis was carried out to determine the effect of subsidence by providing various displacement loads at the base of the building as a representation of various incline angles. The column capacity curve of the axial-moment interaction diagram was parallelly analyzed based on the Indonesian concrete design code [14]. Finally, the influence of the inclined angle on the column state was compared and discussed.

The building chosen as the object of this research is located in Yogyakarta, Indonesia, namely Building E. The function of the building is for educational activities with a total height of about 30 m and consists of 7 floors. The structural system adopts a dual system, Special Moment Frame (SMF), with the shear wall. The soil investigation revealed its condition classified as medium soil. The plan and front view of the building are presented in Fig. 2(a) and Fig. 2(b), whereas the typical column layout of the building is illustrated in Fig. 3.

Fig. 2 depicts that Building E is composed of two identical buildings mirrored on its centerline. Fig. 3 illustrates that the columns of this twin building are identical either the layout or the section type, whereas the core wall is located around the center of the building. The concrete compressive strength used was about 25 MPa with the concrete Young's modulus, E_c = 23,500 MPa. The steel rebar yielding stress was 400 MPa for a diameter of more than 12 mm, and 240 MPa for a diameter of less than 12 mm with the steel Young's modulus, E_s =



(a)

(b)

Fig. 2. (a) Plan view (b) Front view

200,000 MPa. The column dimension, as the object in this research, is presented in Table I. The established 3D building in the numerical model is shown in Fig. 4(a) and Fig. 4(b).

As the central element of a building, columns will be the first element of the upper structure to receive the liquidation impact. Therefore, it is essential to analyze the condition of the building columns while the subsidence occurs. One common way to check is by examining the demand-capacity of the column through the axial-moment interaction diagram. It is well known that the interaction diagram is one way to design and analyze the RC column reinforcement and can also be used to optimize the columns; thus, the design is more effective and efficient [15]. In the special moment frame (SMF), an interaction diagram was utilized to limit a column cross-section. The column cross-section analysis was divided into five conditions.

- Pure compressive load or with small eccentricity.

Table I. Column Dimension

No	*Type*	*Dimension*
1.	K1	800 × 800
2.	K1A	800 × 800
3.	K2	800 × 800
4.	K3	800 × 800
5.	K5	800 × 800
6.	K7	800 × 800

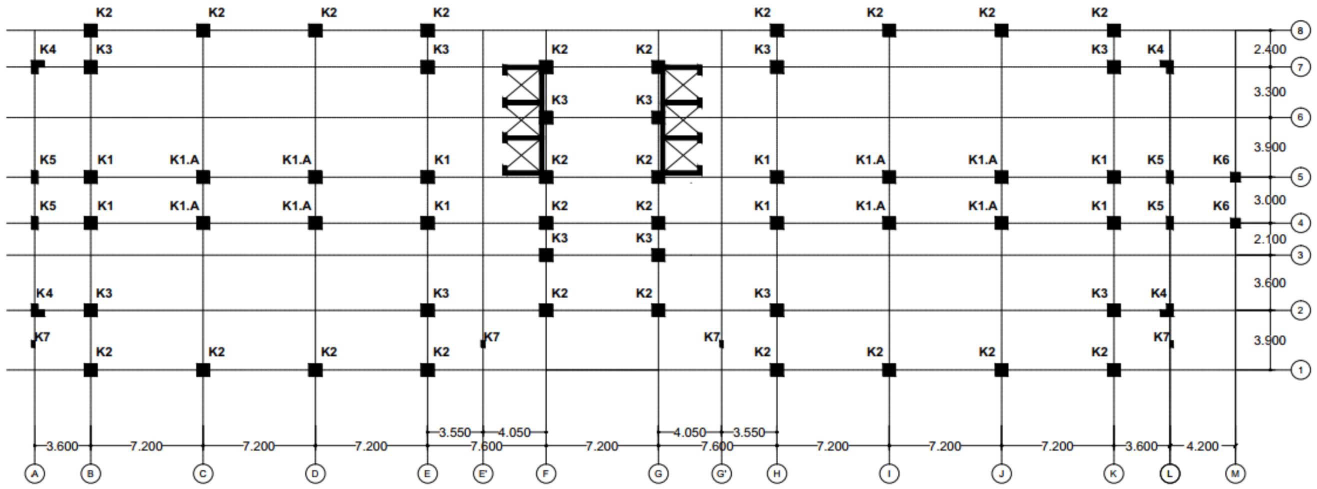
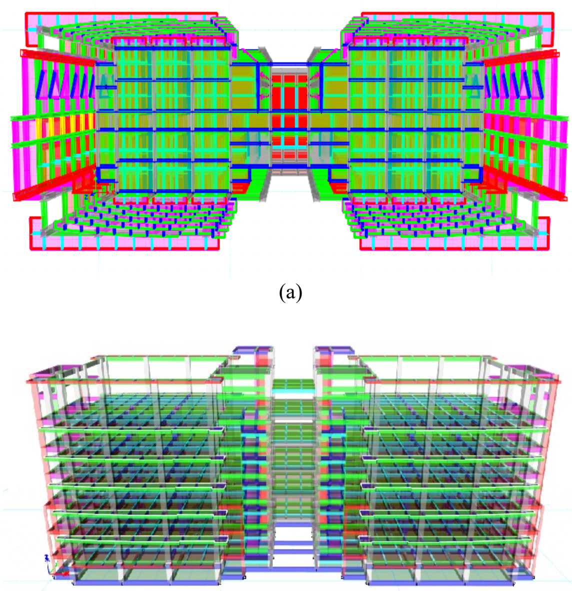


Fig. 3. Column layout of Building E

- tensile reinforcement has reached the yielding state (for f_y = 400 MPa, with ε_t = 0.002) and concrete strain reaching $\varepsilon_t = 0.003$.
- compression rebars have not to yield while the tensile rebars have, when the axial, $P_n = 0$.
- eccentricity exceeds its balanced state, $e > e_b$
- eccentricity below its balanced state, $e > e_b$

Arfiadi states that the interaction diagram analysis by considering the rebar on every four sides of the column is the real condition [16]. Rebar placement with 2 to 4 sides can reduce axial and moment in the cross-section of the column. The shape of the column can also affect its capacity. With the same reinforcement configuration, columns with square shapes tend to have smaller moment capacities than rectangular shapes, but the axial compression does not significantly differ [17]. Nevertheless, square columns can better receive two-way moments than rectangular columns that can only receive large moments from 1-way [18].



(a)

(b)

Fig. 4. 3D numerical model (a) top view (b) front view

3. SUBSIDENCE ANGLE ON BUILDING

As mentioned in the introduction, Muntohar reported that the subsidence occurring at UMY was about 2.5 to 13.5 cm [6]. Therefore, the subsidence trying to be simulated in this research was until 13.5 cm. Only one side of the building was simulated in this case, with another side remained in its position. Hence, the subsidence formed an angle (α) to the horizontal or original level. The α angle of the building would also produce other properties, such as vertical displacement or maximum subsidence (Δ) (see Fig. 6). The relation between subsidence angle (α) and maximum subsidence (β) is shown in Table II.

The earthquake load was designed based on the Indonesian seismic code SNI 1726:2012 [19]. Acceleration values for a short period (S_s) and one second period (S_1) were determined according to the seismic conditions contained in the Indonesia hazard map 2017. The soil type was also considered in determining the designed response spectrum. As regulated inside the provisions, the response spectrum should be adjusted to the shear of the first mode. According to the code, mass participation must reach 90% of the actual mass of each

Table II. The Relation Between Subsidence Angle and Δ

No	α (^{0})	Δ (m)
1.	0.005	0.0064
2.	0.01	0.0127
3.	0.02	0.0254
4.	0.04	0.0508
5.	0.1	0.1271

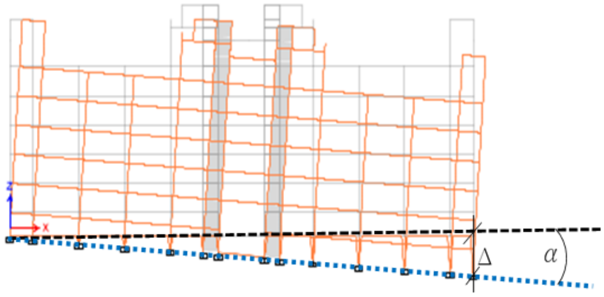


Fig. 5. Incline angle

vocal axes. Moreover, mode 1 of the building was in the *x*-direction with the natural period (T_n) 0.783 s, mode 2 was in torsional direction with T_n = 0.758 s, and mode 3 was in the *y*-direction with T_n = 0.61 s (see Fig. 5).

4. DEMAND-CAPACITY DIAGRAM

Demand-capacity for a column is commonly formed by taking the interaction between axial compression and moment capacity of a column cross-section. Thus, it is also named as an axial-moment interaction diagram, i.e., P-M interaction diagram. The area under the P-M diagram is regarded as the safe zone, and vice versa. Therefore, by plotting the axial and moment force obtained from the simulation to the P-M interaction diagram, the column state can be figured out. During the simulation, while the building suffered subsidence, it was also subjected to the earthquake loads for the lateral force. Once the simulation for all scenarios completed, all axial and moment internal forces in the column were extracted for checking through the interaction diagram.

The plotted force to the axial-moment diagram for each column type is presented in Fig. 7(a) to Fig. 7(f). The $\alpha = 0.1°$ was seen in several K3 columns, in Fig. 7(d), and K7, in Fig. 7(f), it could not bear the internal forces. These were indicated by many plot data exceeded the boundary of P-M interaction for both K3 and K7. If the closer observation was taken primarily for K3, the P-M interaction diagram exceeded at $\alpha = 0.04°$. Hence, several K3 columns would collapse first at $\alpha = 0.04°$. Most of the collapse case occurred in K3 and K7 were due to the increase of moment internal force. These collapses can be seen from the P-M diagram for both K3 and K7, along with the bigger α, the moment force getting more extensive, whereas the axial forces did not have a significant change. Furthermore, it indicated that the collapse criteria for both K3 and K7 were likely to be categorized as bending failure since the major force causing them to fail was the moment forces. Meanwhile, the critical condition was found for the K2 in Fig. 7(c) because, at $\alpha = 0.1°$, some interaction force reached the axial limit. The same condition was also depicted for the K5 column in Fig. 7(e) in which several interaction forces were detected slightly below the interaction limits, implying that this type of column was nearly in a critical state.

Furthermore, other types of columns (K1, K1A) all remained safe, expressed by the data plotted were all under the interaction curve. Moreover, the increase of α did not give a profound effect on the axial and moment interaction forces. It may be caused by the column configuration in which columns

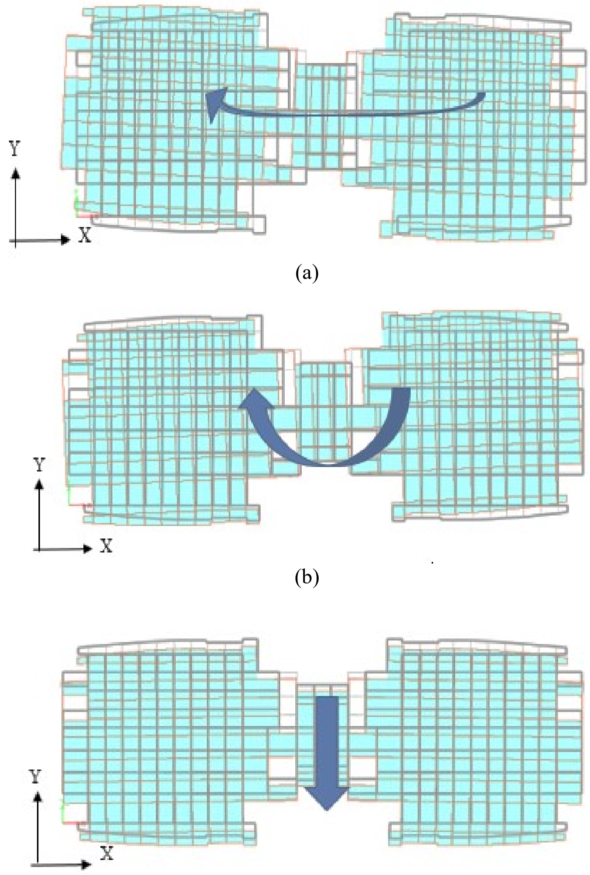


Fig. 6. First 3 modes of building (a) mode 1 (b) mode 2 (c) mode 3

around the center of the building have a bigger chance to share their internal force to both sides, while columns around the perimeter can share to one side only. The column dimension for K1, K1A, K2, and K3 were all the same (800 × 800). However, the K2 and K3 columns suffered greater axial and moment than the K1 and K1A. Besides, the steel rebar configuration would also determine the boundary limit of the P-M curve.

Overall, only K1 and K1A remained safe, while K2 and K5 were both in a critical state; K3 and K7 were categorized as a failure. In other words, all types of columns placed around the center of each side of this twin building did not suffer a significant increase of moment when the largest simulated subsidence angle was applied. In a nutshell, the central column had a higher chance of surviving than the column around the perimeter of the tilted building against the earthquake loads.

5. CONCLUSION

Land subsidence causes great potential damage to buildings. Columns as the primary support of the superstructure will suffer more significant moments due to the tilted building; thus, it is essential to be examined. However, a study discussing the effect of the subsidence angle in an existing building, especially for the column capacity to

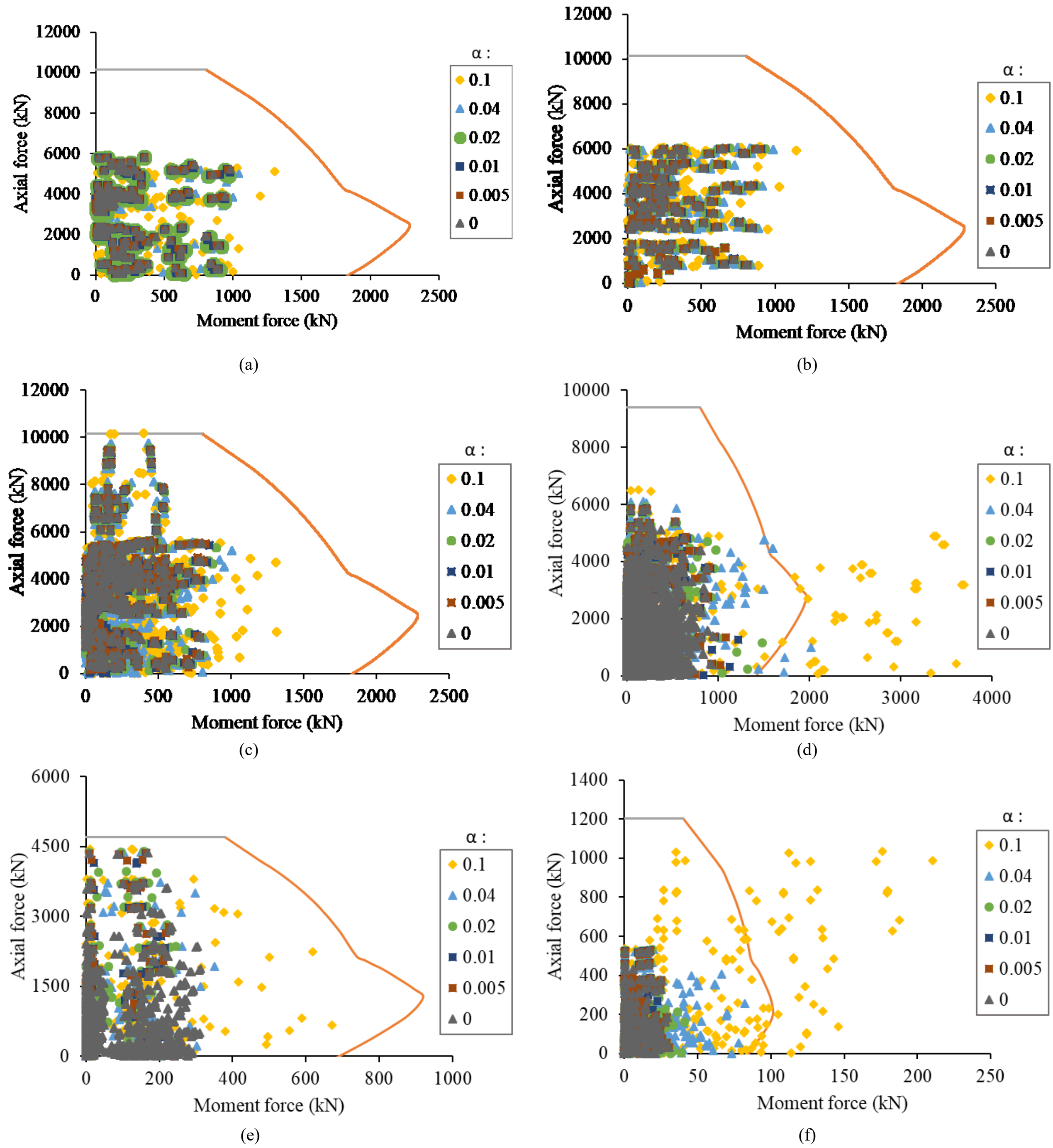


Fig. 7. P-M interaction diagram (a) K1; (b) K1A; (c) K2; (d) K3; (e) K5; (f) K7

withstand the changes of internal forces, is limited. Utilizing the axial-moment interaction diagrams, the effect of the inclined building subsidence became the focus of this paper. The tilted building with subsidence variation angles of about 0.005°, 0.01°, 0.02°, 0.04°, and 0.1° was simulated under the seismic load, and all structural column types of K1, K1A, K2, K3, K5, and K7 were investigated. The analysis results revealed that the moment forces increased along with the rise of the *α*.

About 1.03% of the K3 column exceeded its column capacity at a subsidence angle of 0.04°. At α = 0.1°, about 33.33% of the K7 column could not withstand their capacity, and some columns for K2 and K5 were in a critical state. All types of K1 and K1B columns were still able to withstand the axial and moment force due to the earthquake and the slope of the building. This study highlighted that a column located around the center of the building had a higher possibility than those on the perimeter to bear larger seismic loads, even though the building was tilted.

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