

PRELIMINARY STUDY ON LEANING COLUMN EFFECT CAUSING COLLAPSE OF TEMPORARY SUPPORTS DURING GROUTING IN TAIWAN

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ABSTRACT

In reinforced concrete structures, temporary supports frequently fail during slab grouting instead of after completion. This indicates that the initial design strength of the temporary support is greater than the actual weight of the newly grouted concrete. This study investigates the failure mechanism of temporary support collapses during concrete grouting, based on LeMessurier's theory of the leaning column effect and previous research by Peng et al. on the load-bearing capacity and the leaning column effect in single-story, double-story, and combined scaffold temporary supports. The findings indicate that the collapse mechanism in these temporary supports during concrete grouting is primarily driven by the leaning column effect, which significantly reduces the critical loads of the overall structural system. The leaning column will induce the leaning column effect in the compression structural system, thereby significantly reducing the critical load of the overall structural system. This study examines the three types of temporary supports and explains how the failure mechanism of the leaning column effect influences the reduction of critical loads on the overall structures. Moreover, this study collected actual collapse instances of the three previously mentioned types of temporary supports to illustrate how the failure mechanism associated with the leaning column effect results in the collapse of the temporary support during the grouting process. Proposals for improving assemblies of three temporary supports were also made. When designing temporary supports, it's essential to change the unrestrained boundary condition of the structural system to a restrained one to eliminate the leaning column effect.

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1. Introduction

The setup of temporary supports in construction varies based on the headroom of buildings. In Taiwan, three typical setups are used: a single-story temporary support, a double-story temporary support, and a combined assembly of tubular steel scaffolds with other supports (referred to as a combined scaffold temporary support). For the headroom below 4 m, single-story temporary supports, typically using tubular steel adjustable shores or wooden shores, are predominant, as shown in Fig. 1. Double-story temporary supports are often chosen for cost savings for the headroom between 4 and 7 m, primarily utilizing tubular steel adjustable shores, as illustrated in Fig. 2.

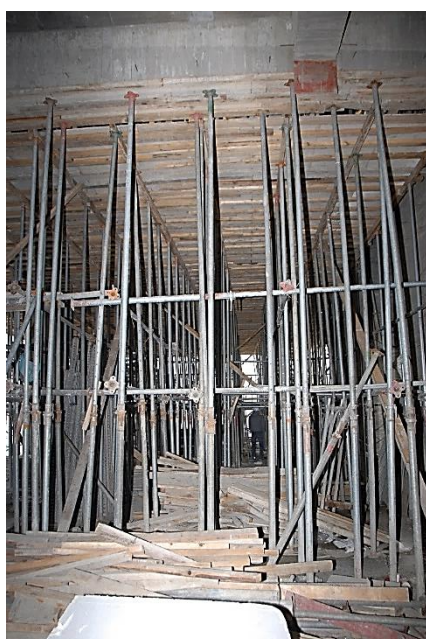


Fig. 1 A single-story temporary support on a construction site in Taiwan

When the headroom exceeds 7 m, temporary supports typically employ a combination of tubular steel scaffolds with wooden shores or tubular steel adjustable shores, which is referred to as a "combined scaffold temporary support" for simplicity. The steel scaffold, a standard material, has a unit height of 1.7 m. After stacking the scaffolds several stories vertically, if the gap between the top of the scaffold and the bottom of the slab is less than 1.7 m, contractors fill this space with wooden shores or tubular steel adjustable shores, creating a hybrid assembly, as shown in Fig. 3.



Fig. 2 A double-story temporary support on a construction site in Taiwan

Steel structure design codes consider live loads, dead loads, seismic forces, and wind loads. [1–4] During construction, the primary external load is the weight of grouted fresh concrete, with secondary loads including rebar, formwork, personnel, equipment vibrations, etc. In Taiwan, investigations into construction accidents show that temporary support collapses are not linked to earthquakes or typhoons. As a result, current design practices typically do not consider seismic or wind forces.

Since temporary supports are temporary structures that are removed immediately after construction, their importance is often overlooked. To date, the temporary support design in Taiwan typically follows steel structure design

codes, applying the ASD concept with increased safety factors. For smaller construction projects, temporary supports are often built based on the experience of on-site workers.

The setups for temporary support differ from those for traditional steel structures. Temporary supports commonly use pin connections, while steel structures rely on high-tension bolts and welding. Furthermore, because of variations in construction accuracy and the construction environment, it is unsuitable to directly apply steel structure design specifications for designing temporary supports.

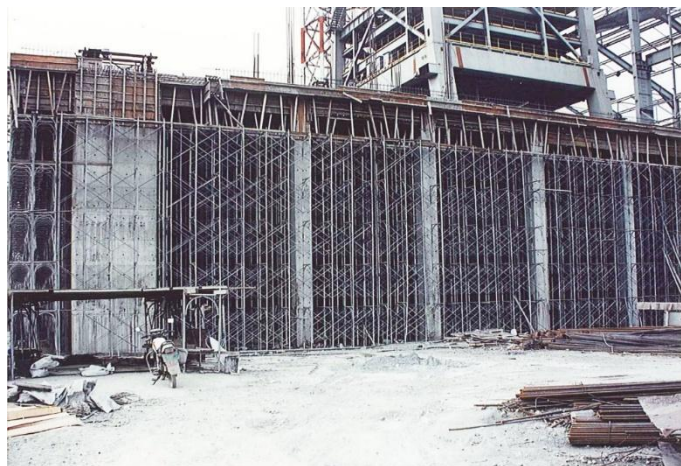


Fig. 3 A combined scaffold temporary support on a construction site in Taiwan

Collapses of temporary supports are not uncommon. For example, on January 28, 1997, a single-story temporary support collapsed during slab grouting at the box culvert on Second Expressway in Kaohsiung, Taiwan, resulting in one death and one severe injury (Fig. 4). On December 17, 2006, during grouting at the Linkou residential project in Taipei, Taiwan, a double-story temporary support collapsed, killing five workers beneath the fallen reinforced concrete slab (Fig. 5). On October 4, 1998, another incident took place at the Chiayi Hospital construction site. During grouting, a temporary support system that combined scaffolds and tubular steel adjustable shores collapsed, resulting in one fatality and six injuries (Fig. 6).

Reviewing these collapse cases and earlier studies [5] shows that temporary support failures primarily occur during concrete pouring. This indicates a connection between these failures and the design of the temporary supports. For example, if a professional engineer determines that the structural strength of temporary support is 100 tonnes, using a safety factor of 2 results in a design strength of 50 tonnes. This indicates that the temporary support must bear 50

tonnes of grouted fresh concrete.

However, if the temporary support collapses when only half of the slab is grouted, the weight of the grouted fresh concrete is approximately 25 tonnes. This indicates that the weight of the grouted fresh concrete is only one-fourth (i.e., 25/100) of the initially calculated strength of the temporary support. Further investigation is needed to understand why the initially calculated strength of the temporary support differs significantly from the actual weight of the grouted fresh concrete. We could start by examining how the leaning column effect influences the strength of the temporary support. [6]

A considerable amount of research has been conducted on steel scaffolds. For instance, Jake and Chan (2020) [7] employed the second-order analysis to investigate the mechanical behavior of scaffolding structures, confirming how uneven subsidence affects their ultimate load capacity. In a separate study, Jake and Chan (2019) [8] conducted a direct analysis to examine the ultimate load capacity of scaffolding structures featuring asymmetrical joints. Liu et al. (2010) [9] performed load tests on scaffolding structures reinforced with large X-braces, demonstrating the relationship between the X-brace and the load-bearing capacity of the scaffolds. Peng et al. (2021) [10] examined how inclined top and bottom boundary conditions influence the ultimate load of scaffolding structures.



Fig. 4 Collapse of single-story temporary support at the box culvert on Second Expressway in Kaohsiung, Taiwan

Tubular steel adjustable shore remains intact and undamaged



Fig. 5 Collapse of double-story temporary support at the Linkou residential project in Taipei, Taiwan

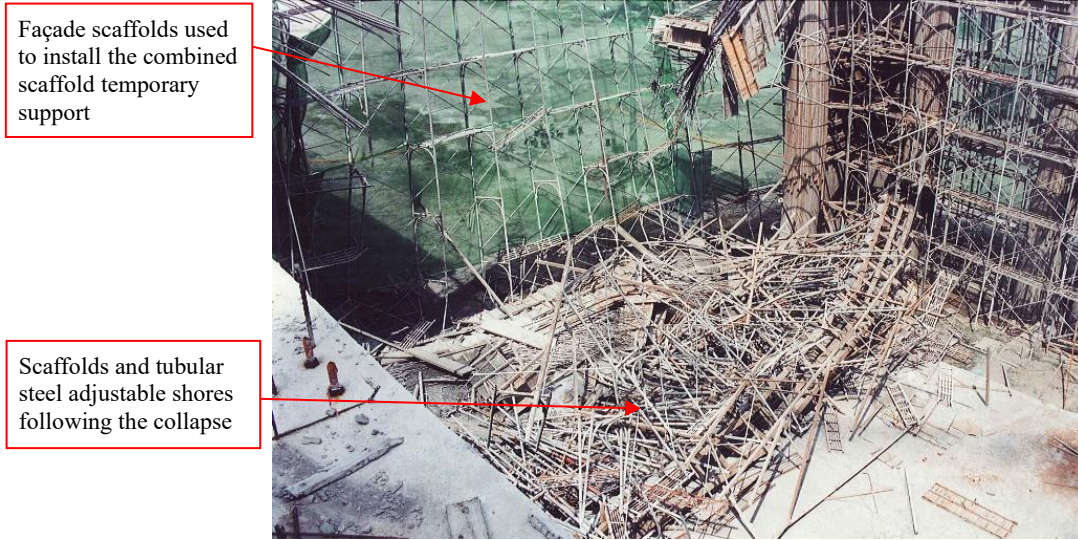


Fig. 6 Collapse of a combined scaffold temporary support at the girder of a hospital construction project in Chiayi, Taiwan

For research on steel scaffolds used in conjunction with other shores, Peng et al. (2020) [11] conducted full-scale outdoor loading tests on systems that combine steel scaffolds with wooden shores. This study compared the load-bearing capacity and failure modes of scaffolding structures with those of combined scaffolding assemblies. Earlier studies by Peng et al. (1998) [12] and Peng et al. (1996) [13] examined the mechanical behavior of these combined scaffolding assemblies. Their findings suggested that wooden shores or tubular steel adjustable shores positioned above the scaffolds could function as leaning columns. The longer these columns are, the more they reduce the overall critical load capacity of the combined scaffolding assemblies.

Research on temporary supports for single-story and double-story assemblies is less extensive than studies on steel scaffolds. Among the few studies on single-story assemblies, Peng (2013) [14] investigated the mechanical behavior of individual tubular steel adjustable shores, emphasizing their column buckling curve and reinforcement within structural systems. Peng (2012) [15] examined the ultimate load capacities of wooden shore systems under various top and bottom boundary conditions and those of combined systems that include both wooden shores and tubular steel adjustable shores. Peng (2002) [16] explored the theoretical relationship between single-story assemblies and the leaning column effect, tentatively concluding that merely increasing the number of leaning columns does not significantly enhance the critical loads of the entire single-story systems.

Peng (2010) [17] examined the critical loads of various temporary supports for wooden double-story assemblies and their reinforcement configurations. Additionally, Peng (2002) [18] conducted a preliminary theoretical exploration of the relationship between double-story assemblies and the leaning column effect. Similar to single-story assemblies, the research indicated that merely adding more leaning columns in double-story assemblies does not significantly enhance the total critical load.

Previous studies on steel scaffolds indicate that most focus solely on analyzing and testing the mechanical behavior of basic scaffolding assemblies, while few investigate combined scaffolds with top shores. These studies revealed that the leaning column effect reduces the critical load of combined scaffolds with top shores. Likewise, the leaning column effect impacts both single-story and double-story assemblies with unrestrained boundaries, and their overall critical loads do not increase with the addition of more leaning columns. The leaning column effect offers essential insight into why temporary supports frequently fail during concrete grouting, especially when the original design load of these supports far exceeds the actual load from the grouted fresh concrete.

2. Leaning column effect

The American Institute of Steel Construction (AISC) defines a *leaning column* as "a column designed to carry gravity loads only, with connections that are not intended to provide resistance to lateral loads" [1]. In simple terms, columns within a system that have pinned connections at both their top and bottom ends and do not possess lateral restraints on their boundary conditions are referred to as leaning columns. Below is a brief explanation of how the leaning column effect occurs.

A perfectly straight column, when subjected to axial load, will buckle once

this load reaches the column's critical load (P_{cr}). The critical load P_{cr} depends on the material, cross-sectional shape, length, and boundary conditions of the column. The critical load of the column is represented by Eq. (1). [19]

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} = \frac{P_e}{K^2}, \quad (1)$$

where

L : Length of the column;

E : Young's modulus of the column;

I : Moment of inertia of the column section;

K : Effective length factor of the column and

P_e : Euler buckling load $P_e = \pi^2 EI / L^2$ with $K=1.0$.

If the boundary conditions of a column change, its critical load will also change. For example, as illustrated in Fig. 7(a), for Column AB, the calculated effective length factor K_{AB} is 2. Substituting this effective length factor into Eq. (1) results in the critical load of this column, $P_{AB,cr1} (= P_e/2^2) = P_e/4$.

Fig. 7(b) shows an anti-symmetric frame. During compression, the effective length factor K_{AB} for Column AB in this frame remains 2, just like for Column AB in Fig. 7(a). Substituting the effective length factor into Eq. (1) produces the critical load for Column AB, $P_{AB,cr2} = P_e/4$, as demonstrated in Eq. (2). Eq. (3) illustrates the total critical load of the frame in Fig. 7(b) at the point of buckling, $P_{cr2} = P_e/2$.

$$P_{AB,cr2} = \frac{\pi^2 EI}{(2L)^2} = \frac{P_e}{(2)^2} = \frac{P_e}{4} = P_{AB,cr1} \quad (2)$$

$$\Sigma P_{cr2} = 2P_{AB,cr2} = 2 \frac{P_e}{4} = \frac{P_e}{2} \quad (3)$$

LeMessurier [6] was the first to introduce the concept of the leaning column effect. In a compressed structural system with unrestrained boundaries, columns with pinned connections at both ends (i.e., leaning columns) create the leaning column effect. This leaning column effect reduces the critical load of non-leaning compressed columns.

LeMessurier introduced a modified effective length factor K' to design columns affected by a leaning column effect within a structural system. The modified K' in the LeMessurier formula is represented in Eq. (4). [20]

$$K' = \sqrt{\frac{P_e}{P_l} \times \frac{\sum P}{\sum P_{eK}}}, \quad (4)$$

where

K' : Modified effective length factor of the column that provides sideways resistance;

P_e : Euler buckling load;

P_i : Column axial force contributing to sidesway resistance;

ΣP : Axial loads on every column in a story;

ΣP_{ek} : Euler loads for all columns in a story provide sidesway resistance for the frame, which is evaluated using the effective length derived from the nomograph.

The leaning column effect in the LeMessurier formula is illustrated by the frame in Fig. 7(c). Figs. 7(b) and 7(c) showcase two different types of portal frames. The only difference is the connection at point C of column CD on the right side; all other assumptions remain the same. At point C, the top of column CD changes from a rigid joint in Fig. 7(b) to a hinged joint in Fig. 7(c). In the system with an unrestrained boundary illustrated in Fig. 7(c), column CD acts as a leaning column.

In the frame depicted in Fig. 7(c), after undergoing compression loads, the leaning column effect increases the effective length factor K_{AB} of column AB. According to the LeMessurier formula (Eq. 4), $K_{AB} = 2.0$ increases to $K'_{AB} = 2\sqrt{2}$ as calculated in Eq. (5). Subsequently, the critical load of column AB is reduced to $P_{AB,cr3} = P_e/8$, as indicated in Eq. (6). The critical load for the entire frame is $\Sigma P_{cr3} = P_e/4$ at buckling, as shown in Eq. (7) in Fig. 7(c).

$$K'_{AB} = \sqrt{\frac{P_e \cdot \Sigma P}{P_1 \cdot \Sigma P_{ek}}} = \sqrt{\frac{P_e \cdot \frac{2P}{P} \cdot \frac{P_e}{\left(\frac{P_e}{2} + \frac{P_e}{(\infty)^2}\right)}}}{\frac{P_e}{P} \cdot \frac{2P}{P}} = \sqrt{\frac{P_e \cdot \frac{2P}{P}}{\frac{P_e}{P} \cdot \frac{P_e}{4}}} = 2\sqrt{2} \quad (5)$$

$$P_{AB,cr3} = \frac{P_e}{(2\sqrt{2})^2} = \frac{P_e}{8} \quad (6)$$

$$\Sigma P_{cr3} = 2P_{AB,cr3} = 2 \cdot \frac{P_e}{8} = \frac{P_e}{4} \quad (7)$$

Eq. (8) provides a comparison of the total critical loads between frame (c) and frame (b) as depicted in Fig. 7. Because of the leaning column effect, the ratio of ΣP_{cr3} to ΣP_{cr2} is 1/2, indicating that the overall critical load of the frame in Fig. 7(c) is half that in Fig. 7(b).

$$\Sigma P_{cr3} / \Sigma P_{cr2} = (P_e/4) / (P_e/2) = 1/2 \quad (8)$$

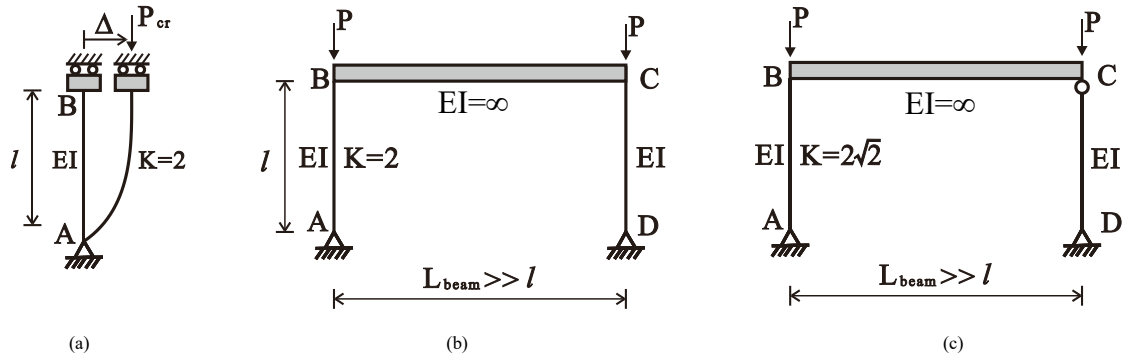


Fig. 7 K values of compression members and leaning columns in different structures

3. Relationship between the leaning column effect and temporary support failures

3.1. Single-story temporary support

Fig. 8 shows the arrangement of single-story temporary support using tubular steel adjustable shores at construction sites in Taiwan. The top of the tubular steel adjustable shore directly supports the wooden formwork of the slab, while the bottom rests on the ground. Since neither end is reinforced, these tubular steel adjustable shores cannot withstand bending moments at the top and bottom and are considered pinned ends in the analysis. If the structural system is unrestrained at the boundaries, each isolated tubular steel adjustable shore can be viewed as a leaning column. Additionally, construction crews employ horizontal ties to connect multiple tubular steel adjustable shores in two

perpendicular directions on the horizontal plane. These tied tubular steel adjustable shores can be regarded as an equivalent strong column, as illustrated in Fig. 8.

Fig. 9 is a schematic diagram depicting a two-dimensional simplified model that simulates a single-story temporary support at a construction site. It illustrates the relationship between a rigid slab, seven leaning columns, and one equivalent strong column. Fig. 10 explains the buckling behavior between leaning columns and the equivalent strong column under load in the single-story temporary support. According to stability theory, when a structural system undergoes buckling and reaches a state of neutral equilibrium, the critical load P_{cr} remains constant. Based on the small displacement theory, the horizontal displacement of the slab in the structural system can take any value at this load point.

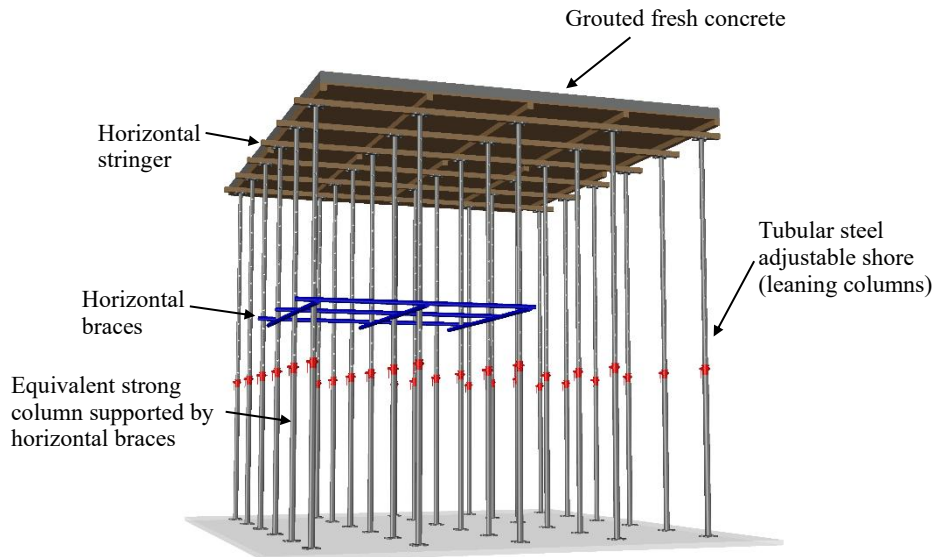


Fig. 8 Schematic diagram of leaning columns and equivalent strong columns in a single-story temporary support

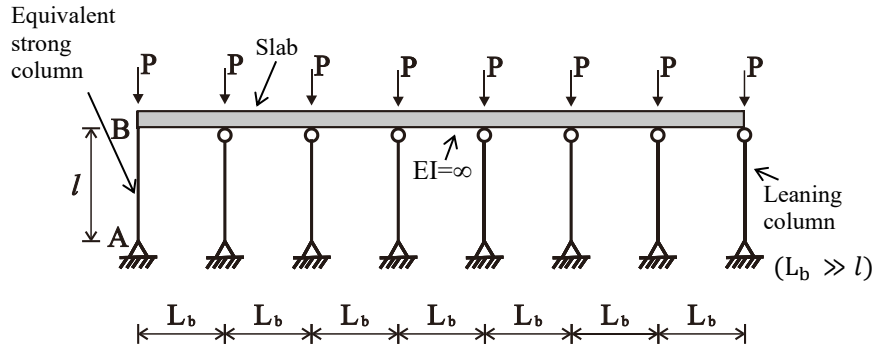


Fig. 9 Schematic diagram of a simplified model for single-story temporary support with unrestrained boundaries, showing leaning columns and an equivalent strong column

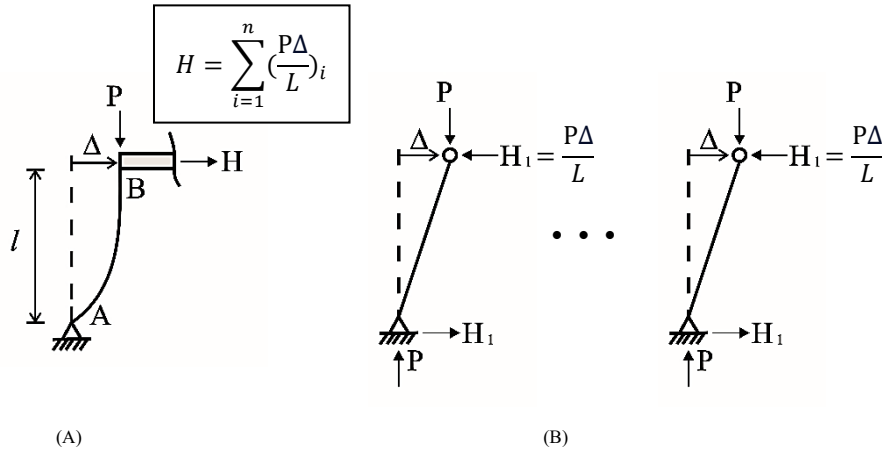


Fig. 10 Schematic diagram of a horizontal force induced by leaning columns in a simplified model for single-story temporary support with unrestrained boundaries

Fig. 10 shows the force equilibrium relationship of each column in Fig. 9 after being loaded. Fig. 10 also shows that the horizontal force H_i , caused by the leaning column effect in the simplified model of a single-story temporary support, is $P\Delta/L$. As shown in Fig. 10, the equivalent strong column AB generates a horizontal force H at its top due to the leaning column effect. This horizontal force H represents the total of all horizontal forces generated by all leaning columns, as expressed in Eq. (9):

$$H = \sum_{i=1}^n \left(\frac{P\Delta}{L}\right)_i = 7\left(\frac{P\Delta}{L}\right) \quad (9)$$

In Eq. (9), P represents the buckling load P_{cr} , which remains constant when the structural system reaches buckling. L denotes the length of the column, and n refers to the number of leaning columns, which is seven. In a state of neutral equilibrium, the horizontal displacement Δ can assume any value; thus, as it increases, the horizontal force H also increases. As the horizontal force H applied to the top of the equivalent strong column AB increases, the critical load of column AB decreases. Hence, an increase in the number of leaning columns within the structural system leads to a larger total horizontal force resulting from buckling deformation, which subsequently reduces the critical load of the equivalent strong column [16].

In the example of seven leaning columns and one equivalent strong column from Fig. 9, the modified effective length factor for the equivalent strong column AB is $K'_{AB} = 4\sqrt{2}$, as shown in Eq. (10). Substituting $K'_{AB} = 4\sqrt{2}$ into Eq. (1) yields the critical load of the equivalent strong column AB, $P_{e,cr4}$, as indicated in Eq. (11). Consequently, the total critical load of the structural system can be calculated as $P_e/4$, as shown in Eq. (12).

$$K'_{AB} = \sqrt{\frac{P_e}{P_1} \cdot \frac{\Sigma P}{\Sigma P_{ek}}} = \sqrt{\frac{P_e}{P} \cdot \frac{8P}{\left(\frac{P_e}{2} + 7 \cdot \frac{P_e}{(\infty)^2}\right)}} = 4\sqrt{2} \quad (10)$$

$$P_{AB,cr4} = \frac{P_e}{(4\sqrt{2})^2} = \frac{P_e}{32} \quad (11)$$

$$\Sigma P_{cr4} = 8 \cdot P_{AB,cr4} = 8 \cdot \frac{P_e}{32} = \frac{P_e}{4} \quad (12)$$

As shown in Eq. (13), comparing the overall critical load of the rigid frame in Fig. 9 with that in Fig. 7(b) indicates that, because of the leaning column effect, the ratio of ΣP_{cr4} from Eq. (12) to ΣP_{cr2} from Eq. (3) is 1/2. This means that the overall critical load of the rigid frame in Fig. 9 is half that in Fig. 7(b).

$$\Sigma P_{cr4} / \Sigma P_{cr2} = (P_e/4) / (P_e/2) = 1/2 \quad (13)$$

The result of the calculation for Eq. (13) matches that of Eq. (8), indicating that the structure with one leaning column shown in Fig. 7(b) and the structure with seven leaning columns depicted in Fig. 9 both have the same overall critical load. As illustrated in Fig. 9, merely increasing the number of leaning columns to seven in the single-story temporary support does not significantly enhance the overall critical load of the structural system.

Alternatively, if we calculate the total critical load of the structure shown in Fig. 9 using the critical load $P_{AB,cr1}$ ($= P_e/4$) for a single column AB, as illustrated in Fig. 7(a), the total critical load for Fig. 9 will be $\Sigma P'_{cr4}$ ($= 2P_e$), as indicated in Eq. (14). If a design safety factor of 2 is applied, $\Sigma P'_{cr4,design}$ ($= P_e$), is calculated as demonstrated in Eq. (15). The actual critical load ΣP_{cr4} in Eq. (12) is one-fourth of the design critical load $\Sigma P'_{cr4,design}$ in Eq. (15), which is calculated as indicated in Eq. (16).

$$\Sigma P'_{cr4} = 8 \cdot (P_e/4) = 2P_e \quad (14)$$

$$\Sigma P'_{cr4,design} = \Sigma P'_{cr4} / S.F. = 2P_e / 2 = P_e \quad (15)$$

$$\Sigma P_{cr4} / \Sigma P'_{cr4,design} = (P_e/4) / (P_e) = 1/4 \quad (16)$$

Considering the fresh concrete grouted on the single-story temporary support illustrated in Fig. 9, the leaning column effect reveals that the structure attains its critical load when the grouted concrete reaches one-fourth of the design load. This leads to an immediate buckling collapse due to minor disturbances affecting the single-story temporary support.

In summary, columns with pinned ends can be regarded as leaning columns in the single-story temporary support with unrestrained boundaries. During buckling, the leaning column effect significantly reduces the overall critical load of the structural system. However, if the single-story temporary support is adjusted to fit the restrained boundaries, the leaning column effect will disappear, as shown in Fig. 11. The effective length factor of the equivalent strong column AB will change from ≥ 1 to ≤ 1 . The original 'leaning columns', with pinned ends and unrestrained boundaries, will have their effective length factor changed from ∞ to 1.0, significantly enhancing the overall critical load of the structural system.

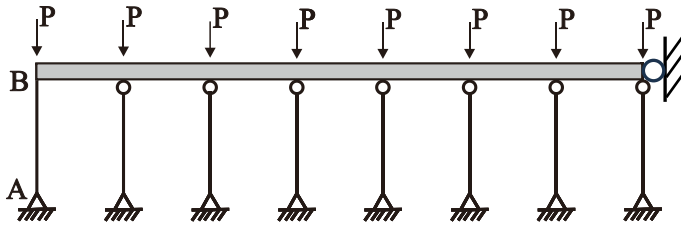


Fig. 11 Schematic diagram of a simplified model with restraint boundary conditions for single-story temporary support to enhance load-bearing capacity

3.1.1. Collapse case of single-story temporary support and leaning column effect

Fig. 12 illustrates the installation of temporary support using single-story tubular steel adjustable shores in the collapse area of the vehicular box culvert across the Second Expressway in Kaohsiung, Taiwan. Fig. 13 shows that the collapsed region of the vehicular box culvert's top slab was 20 m long, 9 m wide, and 1.1 m thick, featuring a temporary support height of 5.3 m. The total weight of the concrete slab supported by the temporary support was approximately 475 tonnes ($= 2.4 \times 20 \times 9 \times 1.1$). The vehicular box culvert was built in two stages, as

illustrated in Fig. 12. The right side was completed first, while work on the left side started one month later. The single-story temporary support on the left side collapsed during the grouting process, as shown in Fig. 4. Fig. 12 also shows the concrete grouting path of the slab on top of the vehicular box culvert.

This project used a single-story temporary support with tubular steel adjustable shores, each measuring 5.3 m in length. These steel shores were neither welded nor bolted at their top and bottom ends, which makes them effectively pinned joints for analysis. If the boundaries of the assembly system are unrestrained, these independent tubular steel adjustable shores can be regarded as 'leaning columns.' Additionally, several tubular steel adjustable shores were linked by multiple horizontal braces, forming a cohesive structure. These braced tubular steel adjustable shores can be regarded as one 'equivalent strong column,' as illustrated in Figs. 12 and 13.

The vertical walls on both sides of the left box culvert in this project have been completed, offering lateral support for the top slab of the temporary support. However, in the perpendicular direction, there were no side walls to provide lateral support for the top slab, as shown in Fig. 14, which illustrates the possible direction of slab displacement. The movement of the top slab in this single-story temporary support can cause the leaning column effect in the structural system, significantly reducing the overall critical load. When global buckling and instability occur, the structure may experience a rapid, domino-effect collapse following a minor disturbance, while most components remain intact until a failure happens. As illustrated in Fig. 4, following the collapse of the temporary support, the outermost tubular steel adjustable shore, which shifted outward, remained intact and was not crushed.

If the engineers missed the reduction in the critical load of the overall structure caused by the leaning column effect when calculating the temporary support strength for the single-layer assembly in this project, it is highly likely that during the grouting process, the weight of the fresh concrete on the top slab would reach the critical load, resulting in structural instability. At this point, the impact force from the pumped fresh concrete on top of the temporary support could cause a minor disturbance, potentially triggering a domino-like collapse of the entire single-story temporary support.

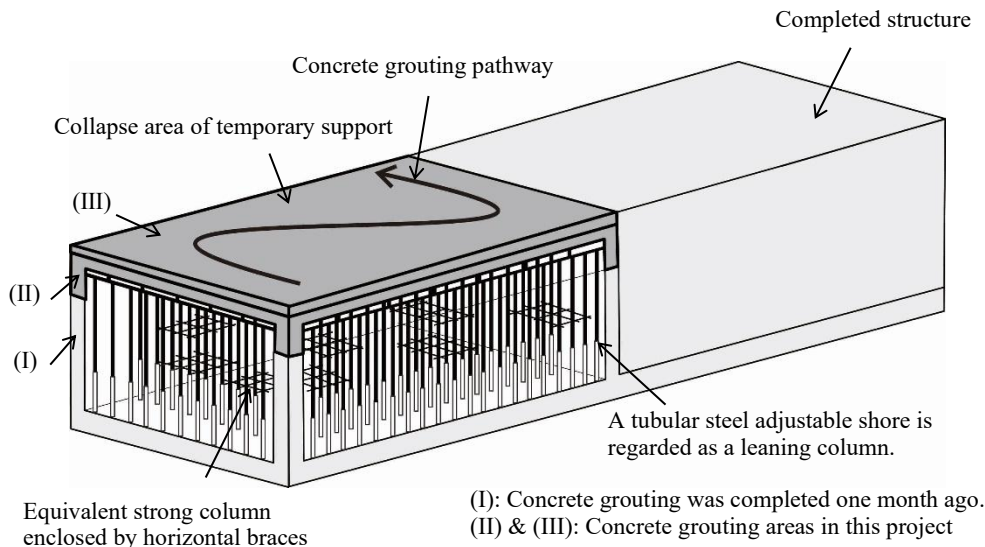


Fig. 12 Schematic diagram depicting the single-story temporary support in the collapse area of the box culvert across the Second Expressway in Kaohsiung, Taiwan

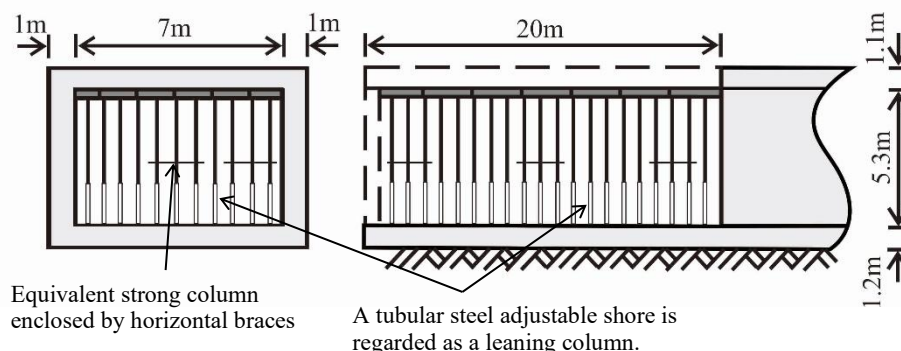


Fig. 13 Front and side views of the single-story temporary support in the collapse area of the box culvert across the Second Expressway in Kaohsiung, Taiwan

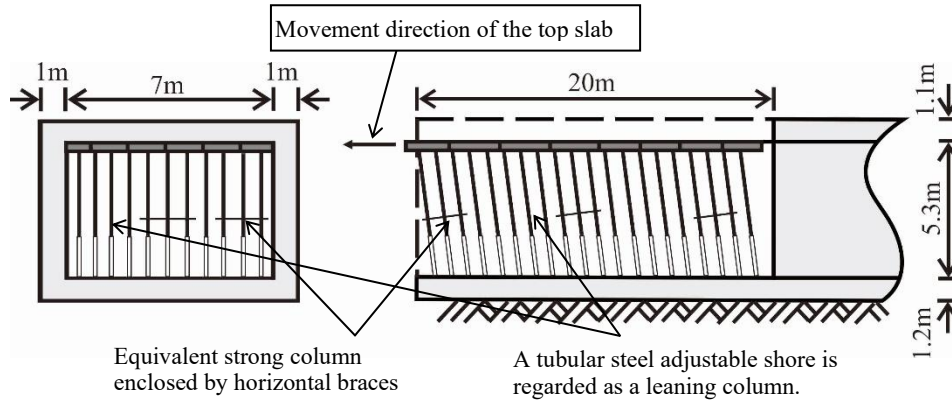


Fig. 14 Schematic diagram illustrating the movement direction at the top slab of unrestrained single-story temporary support in the collapse area of the box culvert across the Second Expressway in Kaohsiung, Taiwan

3.1.2. Improvement strategy

The best way to improve is to remove the leaning column effect. This is accomplished by adding lateral bracing reinforcement to the top slab of the single-story temporary support, converting the top boundary condition from unrestrained to restrained, as shown in Fig. 15. This modification of the load-bearing capability of the single-story temporary support better matches the original design strength.

3.2. Double-story temporary support

In Taiwan, when a building's headroom measures between 4 m and 7 m, construction contractors often choose the more cost-effective double-story temporary supports during the construction process. Fig. 16 shows that the overall double-story temporary support consists of an upper support and a lower support, separated by horizontal wooden stringers arranged in two directions that are perpendicular to each other.

Contractors commonly use tubular steel adjustable shores or wooden shores as vertical support members in double-story temporary supports, just as these shores are utilized in single-story temporary supports. Since the tops and bottoms of individual vertical supports are not reinforced, these ends cannot effectively resist bending moments and are treated as hinges in the analysis. Because of the unrestrained boundaries of the intermediate horizontal stringers, the individual vertical supports in both the upper and lower stories can be regarded as leaning columns. Similar to the single-story temporary support, the stringers installed perpendicular to each other in the horizontal plane are fastened around some upper and lower vertical supports. These secured vertical supports can be regarded as equivalent strong columns. Fig. 16 illustrates the arrangement of these leaning columns and the equivalent strong columns secured by horizontal braces.

The main distinction in the timing of the leaning column effect between double-story and single-story temporary supports is that, with double-story temporary supports, the leaning column effect may happen without any lateral movement at the upper horizontal formwork. This happens because, even though the upper limit of the double-story temporary support is fixed, lateral movement can still occur at the intermediate horizontal stringers, as shown in

Fig. 17.

Fig. 18 illustrates that varying numbers of leaning columns in a double-story temporary support will produce different effective length factors for the compression members. Consider the equivalent strong column AB in the three cases illustrated in Fig. 18. In Fig. 18(a), the equivalent strong column AB has an effective length factor K_{AB} of 2.0 since there are no leaning columns. Figs. 18(b) and 18(c) show that the effective length factor K_{AB} of the equivalent strong column AB rises to 2.7 and 3.7, respectively, when one and three leaning columns are present, owing to the leaning column effect. This leads to a decrease in the critical load of the equivalent strong column AB , as shown in both Fig. 18(b) and Fig. 18(c) [17, 18].

Given the same slab area, comparing the structure with three leaning columns shown in Fig. 18(c) to the one with one leaning column in Fig. 7(c), Eq. (15) calculates the critical load for the equivalent strong column AB in Fig. 18(c) as $P_e/13.69$. Based on this, the total critical load of the structural system can be calculated as $P_e/6.845$, as shown in Eq. (16).

$$P_{AB,cr5} = \frac{P_e}{(3.7)^2} = \frac{P_e}{13.69} \quad (15)$$

$$\Sigma P_{cr5} = 2P_{AB,cr5} = 2 \cdot \frac{P_e}{13.69} = \frac{P_e}{6.845} \quad (16)$$

Dividing the total critical load ΣP_{cr5} of the structure in Fig. 18(c) by the total critical load ΣP_{cr3} of the structure in Fig. 7(c), as shown in Eq. (7), results in the ratio presented in Eq. (17), which is 0.58. This shows that the total critical load of the structure illustrated in Fig. 18(c) has been decreased by 42%.

$$\Sigma P_{cr5}/\Sigma P_{cr2} = (P_e/6.845)/(P_e/4) = 1/1.71 = 0.58 \quad (17)$$

Consequently, double-story temporary supports usually feature more leaning columns than single-story supports within the same grouting area. This leads to a more significant decrease in the overall critical load for double-story temporary supports than for single-story temporary supports.

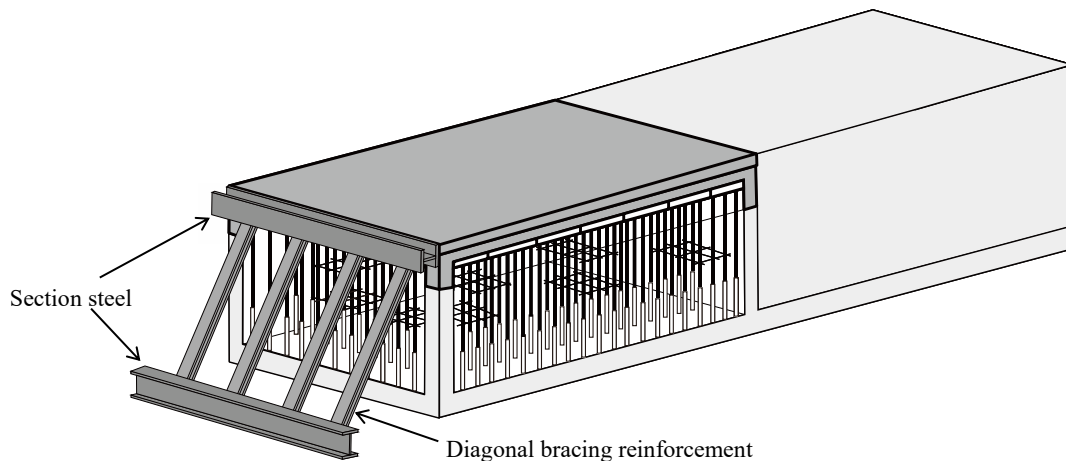


Fig. 15 Schematic diagram illustrating the boundary conditions of the top slab of temporary support in the box culvert across the Second Expressway in Kaohsiung, Taiwan, converted into a restrained system

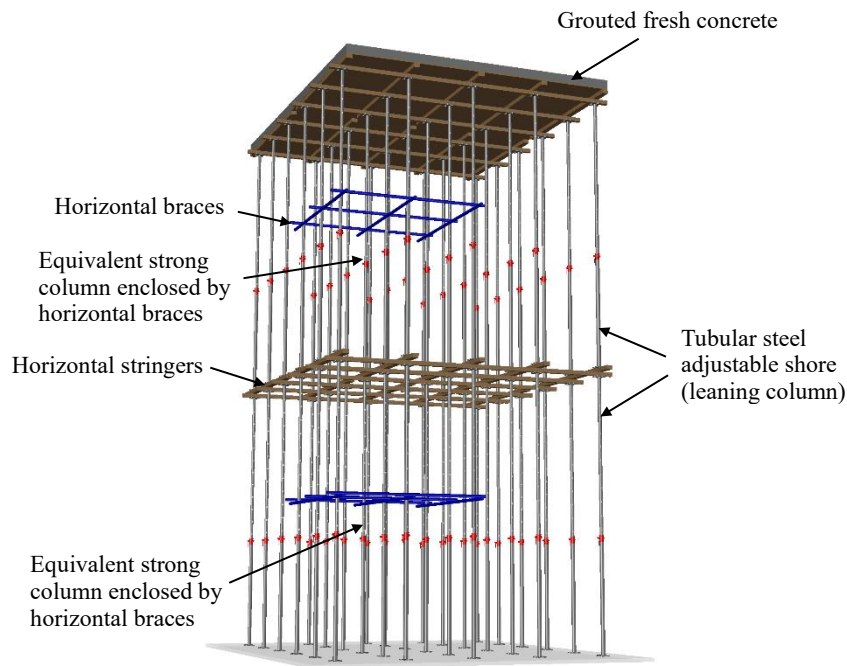


Fig. 16 Schematic diagram showing the arrangement of leaning columns and equivalent strong columns in a double-story temporary support

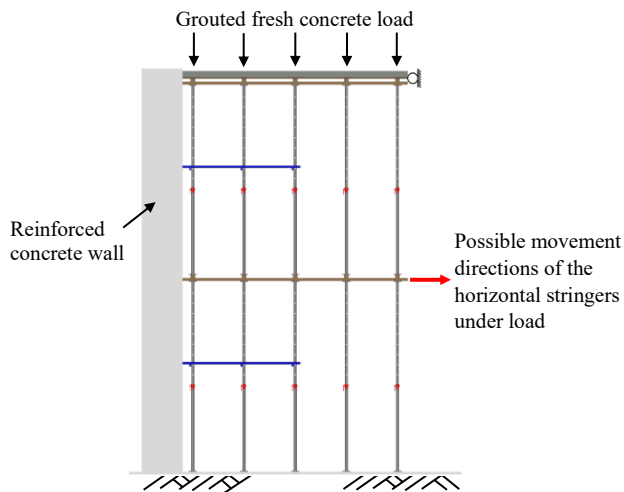


Fig. 17 Schematic diagram of the lateral displacement of horizontal stringers in double-story temporary support under load

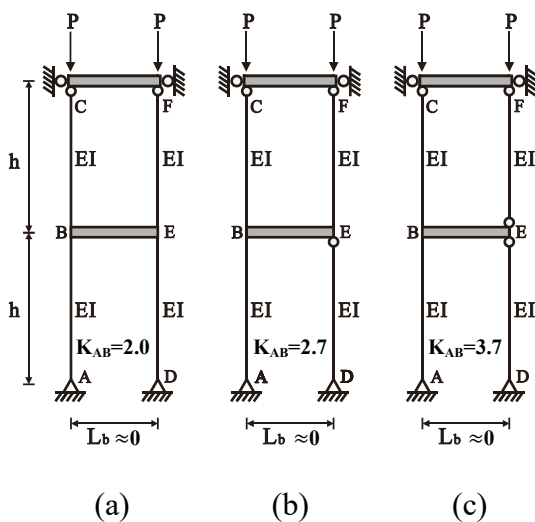


Fig. 18 The effective length factor K_{AB} for equivalent strong columns with different numbers of leaning columns in double-story temporary supports

Transforming unrestrained boundary conditions to restrained ones is more complex for double-story temporary supports than for single-story ones. The intermediate horizontal wooden stringers in double-story temporary supports are 3.6 m long and are typically not connected by opposite joints on-site. As a result, even if the ends of the horizontal stringers, which undergo no displacement, are directly braced against hardened reinforced concrete (RC) walls or columns, these horizontal stringers may shift inward toward the center of the unconnected area when the vertical shores are loaded. This inward horizontal movement of the stringers causes the leaning column effect in the double-story temporary support.

Many years ago in Taiwan, numerous collapses occurred due to the use of double-story temporary supports in residential construction projects. Recognizing the harmful mechanism of the leaning column effect, the Ministry of Labor, as the authority on occupational safety, prohibited the use of double-story temporary supports in urban residential construction. As a result, the temporary support failures in residential construction projects in Taiwan have significantly decreased.

3.2.1. Collapse case of double-story temporary support and leaning column effect

The Linkou residential project in Taipei, Taiwan, utilized a top-down construction method, and Fig. 19 shows the arrangement of double-story temporary supports. The temporary supports utilized tubular steel adjustable shores, and the arrangement of the upper and lower tubular steel adjustable shores resembles that of single-story temporary support. Concrete grouting is set to commence at the building's far end, as illustrated in Fig. 19. The temporary support collapsed instantly during the building's one-sided grouting process, as illustrated in Fig. 5.

The building had a headroom of 595 cm. The double-story temporary support utilized tubular steel adjustable shores, with the lower story height at 334.5 cm and the upper story height at 180.5 cm, as shown in Figs. 19 and 20. In this area, the slab thickness was measured at 20 cm, the beam depth was 60 cm, and the girder depth was 100 cm. The average equivalent thickness of the slab was calculated to be approximately 30 cm, and the total weight of the concrete in the collapsed slab area was about 104 tonnes ($= 2.4 \text{ tonnes/m}^3 \times 18\text{m} \times 8\text{m} \times 0.3\text{m}$).

The double-story temporary support for this project employs horizontal wooden stringers. Insufficient horizontal lateral support at these stringers caused them to shift horizontally after grouting, as depicted in Fig. 21. The moving of the stringers resulted in the leaning column effect within the structural system, significantly reducing the overall critical load of the double-story temporary support and ultimately leading to a collapse.

The failure of the structural system, caused by instability from the leaning column effect, is distinct from the overall failure of the structure due to the yielding of individual components. The double-story temporary support

collapsed from buckling on the construction site, as shown in Fig. 5. Fig. 5 shows that the outermost tubular steel adjustable shores that fell to the ground remain intact and undamaged. This type of failure aligns with the scenario

illustrated in Fig. 4, where the outermost tubular steel adjustable shores in the single-story temporary support remained intact during the instability and collapse.

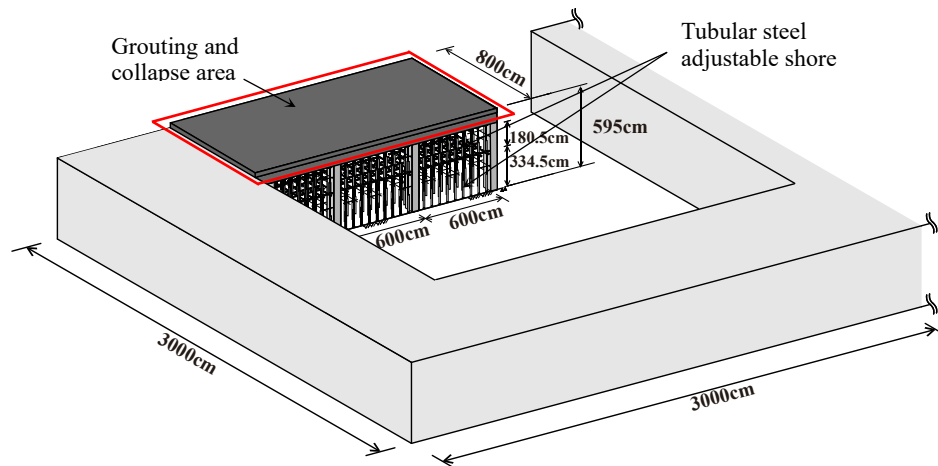


Fig. 19 Schematic diagram of double-story temporary support at the Linkou residential project in Taipei, Taiwan

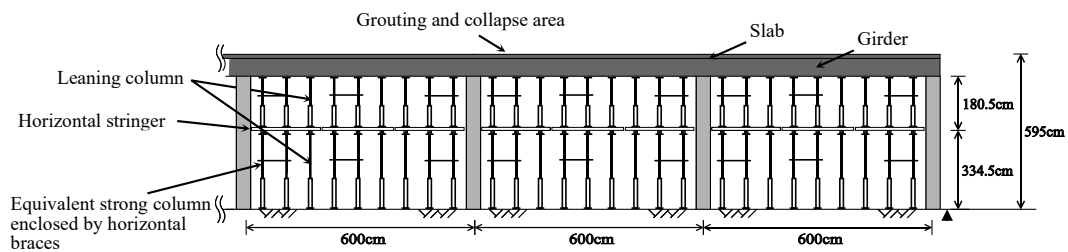


Fig. 20 Front view of the double-story temporary support in the collapse area at the Linkou residential project in Taipei, Taiwan

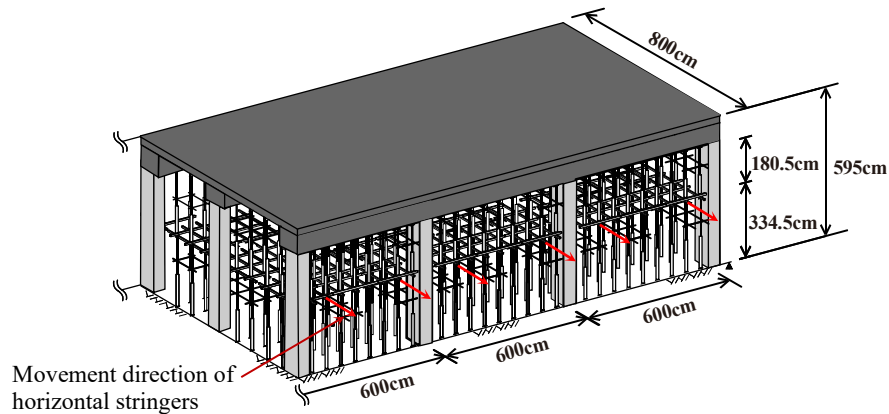


Fig. 21 Schematic diagram of the movement direction of horizontal stringers in a double-story temporary support collapse zone at the Linkou residential project in Taipei, Taiwan

3.2.2. Improvement strategy

It is advised that this project substitutes the double-story temporary support with a straightforward scaffolding system to remove the leaning column effect. Once the grouted fresh concrete is loaded onto the two-story temporary support, the wooden horizontal stringers connecting the upper and lower supports shift outward, causing a leaning column effect. This construction project employed a top-down construction method. Nevertheless, it is practically difficult to reinforce the horizontal stringers in the center of the double-story temporary supports with lateral supports. Additionally, the wooden horizontal stringers are 3.6 m long, and due to cost considerations, these stringers were not connected using opposite joints at the construction site. Therefore, even if the outermost ends are reinforced with lateral supports, the unconnected horizontal stringers will likely shift inward under load, which still leads to the leaning column effect. Therefore, the best approach is to substitute the support material by eliminating the double-story temporary support and employing a steel scaffolding structure that extends straight from the ground to the slab's underside.

3.3. Combined scaffold temporary support

In Taiwan, when the headroom of a building exceeds 7 m, construction contractors often utilize the temporary support made of tubular steel scaffolds in conjunction with other shores (i.e., combined scaffold temporary support), as illustrated in Fig. 22. Fig. 22 illustrates that the overall combined scaffold temporary support consists of two parts: the lower part comprises multiple stories of steel scaffolds, while the upper part includes tubular steel adjustable shores or wooden shores.

Previous studies by Peng et al. [11–13] have demonstrated that the top and bottom ends of tubular steel adjustable shores and wooden shores in the upper section do not resist bending moments. These shores resemble leaning columns in analysis. In a structural system with an unrestrained boundary, leaning columns under compression can lead to the leaning column effect, which decreases the overall critical load of the combined scaffold temporary support. The critical load of the combined system is less than that of a solely installed steel scaffold system.

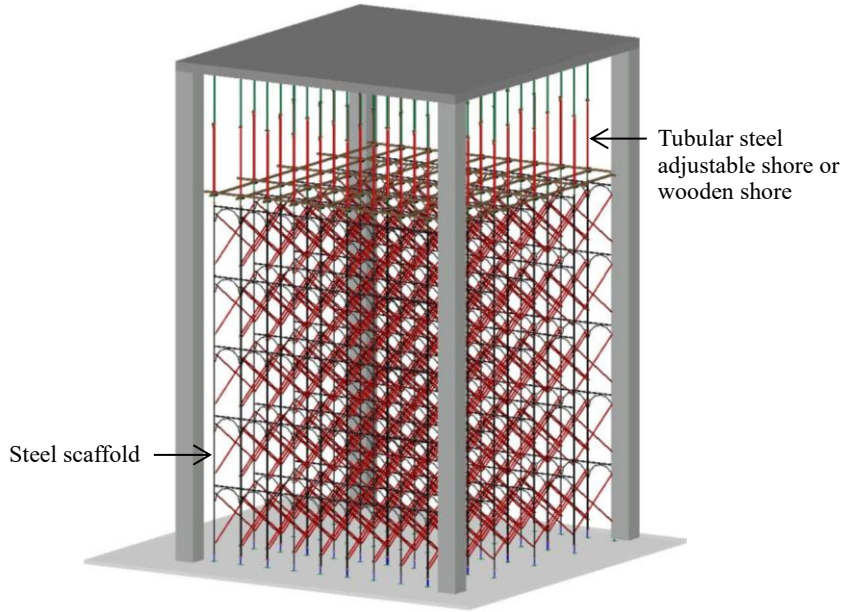


Fig. 22 Schematic diagram of combined scaffold temporary support

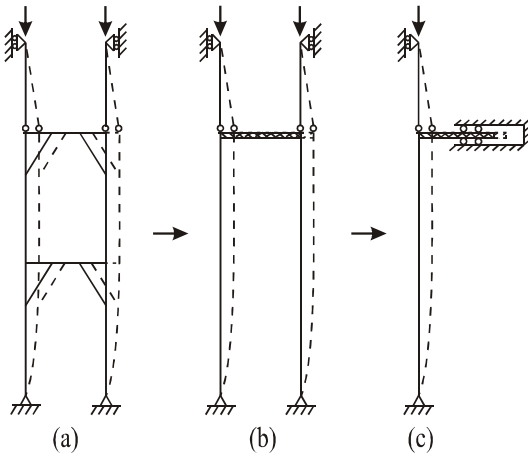


Fig. 23 Simplification process of the double-story combined scaffold temporary support model

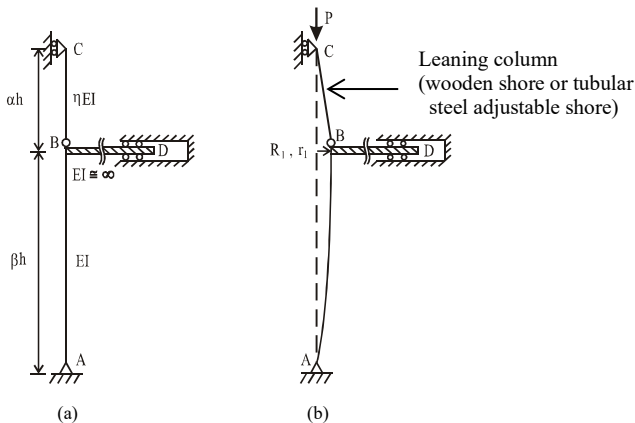


Fig. 24 Parameter definitions and leaning column in the simplified model of combined scaffold temporary support

To examine the mechanical behavior of the combined scaffold temporary support, we can analyze an individual unit from it, as shown in Fig. 22. For simplicity, consider a two-story individual unit of combined scaffold temporary support, as shown in Fig. 23(a). Fig. 23 illustrates the simplification process of a 2D, two-story combined scaffold temporary support model. First, the internal diagonal braces of the scaffolds in Fig. 23(a) are removed to simplify the scaffold stiffness, as shown in Fig. 23(b). Secondly, research by Peng et al. (1998) [12] indicates that the anti-symmetric structural behavior of the

structures shown in Figs. 23(a) and 23(b) under load enables a further simplification of Fig. 23(b) into Fig. 23(c).

Fig. 23(c) illustrates the final simplified model of the two-story combined scaffold temporary support. In this simplified model, the connection between the scaffolds and the upper tubular steel adjustable shores or wooden shores is assumed to permit only horizontal movement. This assumption arises from observing that horizontal stringers are generally fully installed at construction sites, giving them a stiffness greater than that of scaffolds, tubular steel adjustable shores, or wooden shores. In this simplified model, the horizontal stringers can initially be regarded as a rigid body experiencing only horizontal displacement [12].

Fig. 24(a) defines analysis parameters for the simplified model in Fig. 23(c), while Fig. 24(b) illustrates the leaning column effect in this model. In Fig. 24(a), the equivalent stiffness of the scaffolds in the lower AB section is represented as $EI/(\beta h)$. Additionally, the equivalent stiffness of the tubular steel adjustable shore or the wooden shore in the upper BC section is denoted as $\eta EI/(\alpha h)$.

The horizontal stringer BD in Fig. 24(b) can only move horizontally, so the simplified model has one degree of freedom. According to the research conducted by Peng et al. (1998) [12], the critical load of the simplified model of the combined scaffold temporary support, influenced by the leaning column effect, is expressed in Eq. (18) [12]:

$$P_{cr} = \frac{3 \frac{\alpha}{\beta^3} \frac{EI}{h^2}}{1 + \frac{6\alpha}{5\beta}} \quad (18)$$

where

β is the number of scaffolding stories

h is the height of a single scaffolding story (1.7 m)

α is a parameter ranging between 0 and 1

η is a parameter ranging between 0 and 1

In Fig. 24(a), when α and β are both set to 1, the leaning column effect is illustrated through the simplified model of the combined scaffold temporary support depicted in Fig. 25(a). The slope-deflection method can be used to calculate the effective length factor K_{AB} of column AB in the structure shown in Fig. 25(a). The calculated effective length factor K_{AB} for column AB is 2.69 [12].

Fig. 25(b) shows a portal frame from the American Institute of Steel Construction (AISC) design code for steel structures, illustrating the leaning column effect [1, 20]. The effective length factor K_{AB} for column AB in this frame, calculated with the slope-deflection method, is 2.69. Thus, Figs. 25(a) and 25(b) display the same K_{AB} . Additionally, in Fig. 7(c), the modified K'_{AB} ($= 2\sqrt{2}$), derived from Eq. (4) (the LeMessurier formula), serves as an approximate solution for design purposes. Fig. 25 compares two examples that illustrate why the upper tubular steel adjustable shores or wooden shores in a combined scaffold serve as leaning columns. It also clarifies how this leaning column effect impacts the critical load of the combined scaffold temporary support.

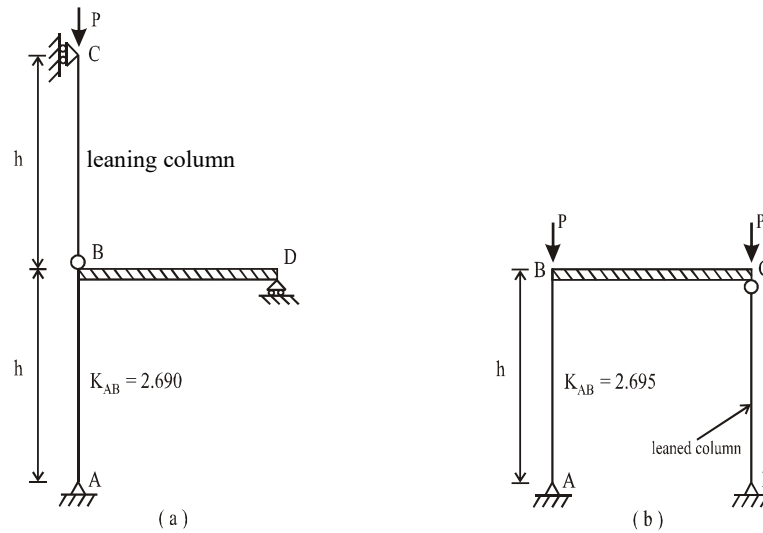


Fig. 25 The leaning column effect relationship between the simplified model of combined scaffold temporary support and the portal frame [12]

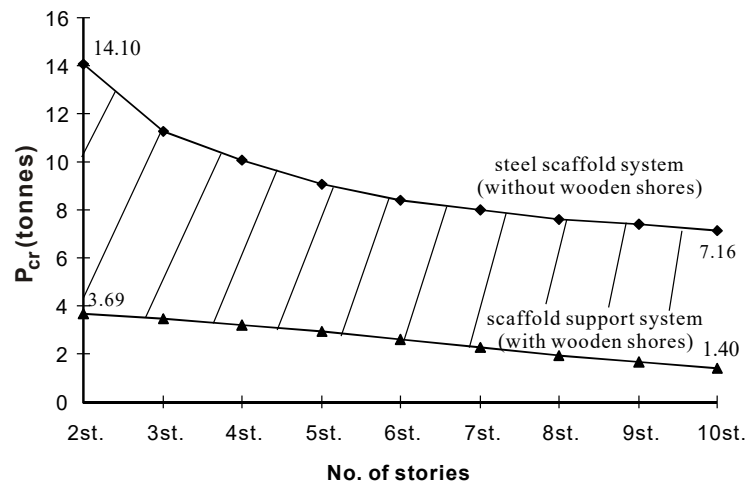


Fig. 26 A comparison of critical loads between scaffold systems with and without wooden shores at the top [13]

According to research by Peng et al. (1996) [13], a comparison of the critical load P_{cr} was conducted using the second-order elastic analysis for two structural systems: (1) a scaffold system without wooden shores and (2) a scaffold system with top wooden shores measuring 1.7 m in length. As shown in Fig. 26, the critical load for a two-story scaffold system without wooden shores is 14.10 tonnes. However, when a 1.7 m long wooden shore is added to the top of the scaffolds, the critical load decreases to 3.69 tonnes. The ratio of the critical load for the two-story scaffold system with wooden shores to that of the two-story scaffold system without wooden shores is approximately 0.3 ($=3.69/14.1$). For a ten-story scaffold system with wooden shores, the critical load ratio compared to one without wooden shores is approximately 0.2 ($=1.40/7.16$) [13].

Fig. 26 shows the differences in critical loads between the scaffold system without wooden shores, which is unaffected by the leaning column effect, and the scaffold system with wooden shores, which is affected by the leaning column effect. The critical load ratios for two-story and ten-story scaffold systems, both with and without wooden shores, are 0.3 and 0.2, respectively. This highlights the significant influence of the leaning column effect on the critical load of combined scaffold temporary supports.

Additionally, when calculating the critical load, it is noted that for scaffold systems exceeding five stories, the ratio of critical loads between systems with and without wooden shores tends to stabilize at a constant value of approximately 0.2. This suggests that, given the same number of stories, the critical load of a scaffold system without wooden shores can be used to estimate the critical load for a scaffold system with wooden shores during the design process. This parameter is necessary because conducting the loading test of the scaffold system without wood shores is easier. The loading test value of the scaffold system without wood shores is multiplied by this parameter to determine the critical load of the scaffold system with wood support.

Additionally, the loading test results for the scaffold system with wooden shores indicate that the wooden shores remained undamaged when the system collapsed due to buckling. Thus, using tubular steel adjustable shores instead of wooden shores results in a similar leaning column effect that impacts the results.

3.3.1. Collapse case of combined scaffold temporary support and leaning column effect

The entrance hall of the hospital in Chiayi, Taiwan, features four girders that enclose an open area designed to support section steels and skylights, as shown in Fig. 27. A combined scaffold temporary support under the three girders consists of steel scaffolds topped with tubular steel adjustable shores. The upper level of this combined scaffold temporary support includes 3.6 m tubular steel adjustable shores, while the lower level consists of two-story steel scaffolds that measure 3.4 m in height. The overall height of this temporary support, including the thickness of the horizontal stringers and U-shaped adjustment seats, is 7.2 m.

The hospital entrance girder is 8.4 m high, 1.2 m deep, and 0.8 m wide. In the collapse area, it measures 18 m long, as shown in Fig. 28. The combined scaffold temporary support assists the reinforced concrete girder, which weighs approximately 41.5 tonnes ($= 2.4 \text{ tonnes/m}^3 \times 0.8 \text{ m} \times 1.2 \text{ m} \times 18 \text{ m}$). In the combined scaffold temporary support, these upper tubular steel adjustable shores can be considered leaning columns. Likewise, the structural system is influenced by the leaning column effect. As shown in Fig. 26, the critical load of the two-story scaffold system with top shores is approximately 0.3 ($=3.69/14.1$) times that of the two-story scaffold system without top shores. The designer may mistakenly evaluate the bearing capacity of the latter structural system while assessing the bearing capacity of the former, which could potentially lead to collapse.

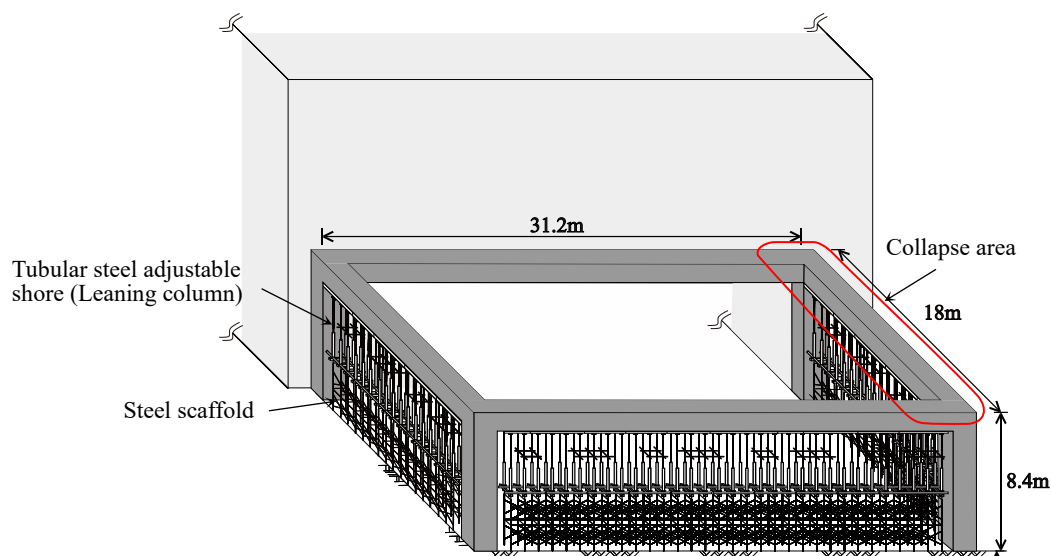


Fig. 27 Schematic diagram of a combined scaffold temporary support at the entrance hall of the hospital in Chiayi, Taiwan

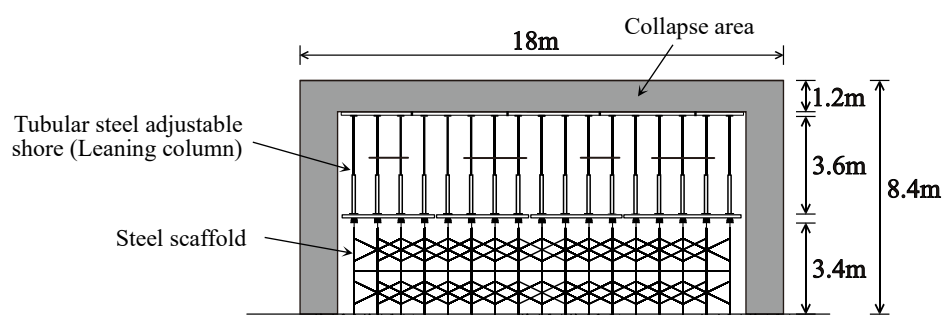


Fig. 28 Front view of the combined scaffold temporary support collapse area at the entrance hall of the hospital in Chiayi, Taiwan

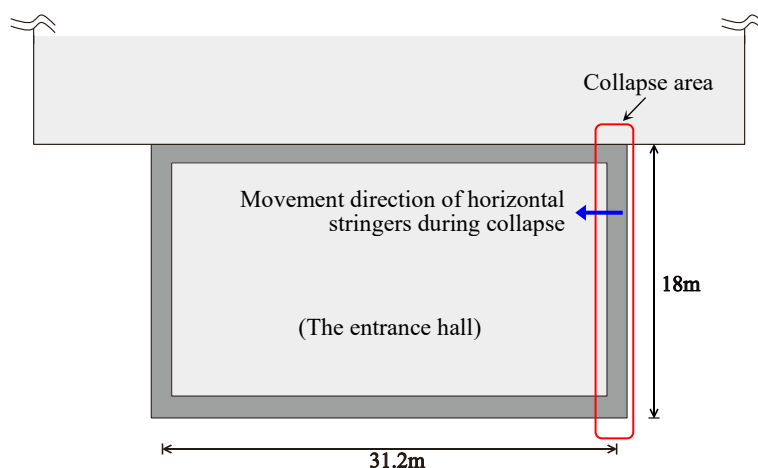


Fig. 29 Schematic diagram of the movement direction of horizontal stringers of temporary support during collapse at the entrance hall of the hospital in Chiayi, Taiwan

After grouting the side girder at this construction site, the combined scaffold temporary support buckled when the grouted fresh concrete reached its critical load. The vibrations from pumping fresh concrete were transmitted to the combined scaffold temporary support. This instability causes rapid deformation, ultimately resulting in collapse, as shown in Fig. 6. Fig. 29 illustrates the movement direction of the horizontal stringers in the combined scaffold temporary support during its collapse.

3.3.2. Improvement strategy

To prevent the combined scaffold temporary support from collapsing, it is advisable to replace the scaffold system with top shores with one without top shores. In simple terms, this means taking out the tubular steel adjustable shores from the upper section of the combined scaffold temporary support and directly extending the scaffold installation down to the bottom of the slabs and beams.

Height differences can be adjusted using the upper and the lower jake bases of scaffolds, effectively eliminating the influence of the leaning column effect.

Fig. 26 shows that using only the steel scaffolding assembly, without the top shores, significantly increases the total critical load of the temporary supports compared to the scaffold system with top shores. Furthermore, to ensure that this scaffold system without top shores can withstand lateral impact forces and to further enhance its overall critical load capacity, it is advisable to add a third row of scaffolds to the existing two-row configuration, resulting in a three-row scaffolding setup.

4. Conclusion

This study investigated the failure mechanisms that lead to the collapse of single-story, double-story, and combined scaffold temporary supports during

concrete grouting at construction sites in Taiwan. The research is based on the theory of the leaning column effect proposed by LeMessurier and the prior studies conducted by Peng et. al. concerning the relationship between temporary supports and the leaning column effect in various temporary support systems. This study finds that the leaning column effect is the primary failure mechanism responsible for the collapse of single-story, double-story, and combined scaffold temporary supports during concrete grouting, as determined through analyses and calculations grounded in stability theory. This paper further examines actual failure cases involving three types of temporary supports: single-story, double-story, and combined scaffold temporary supports in Taiwan. It concludes that the leaning column effect sufficiently explains these failures. The paper proposed several strategies to enhance critical load capacity and prevent collapses, emphasizing that the most effective approach is to eliminate the leaning column effect in structural systems. Professional engineers should modify the boundary conditions of single-story, double-story, and combined scaffold temporary supports from unrestrained to restrained. In other words, the boundary with lateral displacement is replaced by the boundary without lateral displacement. Additionally, it is advisable to avoid double-story temporary support to reduce the risk of collapse.

Acknowledgement

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Conversion factors

1 kg = 1 kgf
 1 kgf = 9.807 N
 1 tonne = 9.807 kN
 9.807 kN = 1000 kg

Reference

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