SAFETY PERFORMANCE OF ONE-LAYER SHORING SYSTEMS USED IN CONSTRUCTION

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Abstract: This paper presents the safety performance of one-layer shoring systems of wood and metal post-shores. The test results indicate that the base stiffness to ground of shores is 50 tonnes-cm/rad for wood post-shores and 70 tonnes-cm/rad for metal post-shores. The system critical loads increase with the numbers of strong shores, but are not affected by the numbers of leaning columns. For simplifying, the LeMessurier formula is used for strength computation of shoring systems. The critical loads of shoring systems increase linearly with the numbers of strong shores, but they are invariant with the positions of strong shores.

Keywords: Falsework, Construction, Leaning column, Post-shore, Shoring

1. INTRODUCTION

The inadequacy of structural strength is the main cause for collapse of falsework in construction based on surveys of construction accidents (Construction Accident Research Reports 1993 ~ 1995). In construction, most reinforced concrete buildings with headroom of 4 to 5 meters use one-layer post-shores as the falsework to support construction loads. These loads arise from fresh concrete, crews, formwork, steel and so on. As shown in Figure 1, two kinds of shores, wood post-shores and metal post-shores, are most widely used in construction. In general, round tubes of metal post-shores are widely used in Taiwan although square hollow sections are occasionally used. Wood post-shores are typically square and used for shoring and re-shoring like metal post-shores.

The criteria used over the past twenty years are not appropriate for current construction, which has increased considerably in the past few decades. In construction sites in Taiwan, the installation of these one-layer shores is always based on the experience of workers since temporary structures are generally considered as secondary importance. The one-layer installation of these shores has a potential danger in construction.

Previous research of post-shores has mainly focused on shoring and re-shoring for multi-story concrete buildings (Chen and Mosallam 1991). For scaffolds, the authors investigated this falsework safety in construction (Peng et al. 1996). This falsework is typically used in structures of headroom greater than 8 meters. For buildings with headroom of 4 to 5 meters, the research on one-layer shores used in construction is limited. The safe use of these falsework systems is a goal of the present research.

2. MATERIAL PROPERTIES AND BASIC ASSUMPTIONS

The material properties of wood and metal post-shores are determined from laboratory tests. For wood post-shores, statically flexible elastic modulus is 127.163 tonnes/cm^2 (12.47 GPa) and area of cross section is 32.881 cm^2. For metal post-shore, elastic modulus is 2040 tonnes/cm^2 (200.1 GPa), area of cross section for upper shore (staff tube) is 3.33 cm^2; and area of cross section for bottom shore (base tube) is 4.02 cm^2.

All boundary conditions in the analyses are based on the site set-up surveyed from actual construction sites in Taiwan. A second-order elastic analysis is used for the numerical calculation. Besides, an equivalent lateral notional disturbing force of 0.1% of total vertical loads is adopted to simulate the initial imperfection of the shoring system.

This paper defines load case A as "Average Load" if the distance between the outermost shore and the slab edge is equal to half of the width between shores. Load case B is defined as "Uniform Load" if the outermost shore is located at the edge of the slab. Figure 2 illustrates these two loading conditions for a 9 (=3×3) shore system.

In analysis of the end stiffness of wood and metal post-shores, the shore length H is assumed to be 3.6 meters as shown in Figure 1. The definition of "End Stiffness" of the wood and metal post-shore is k_{sw} and k_{stb} in Figure 1. Based on experimental test results, the average stiffness of the joint k_{sm} in the metal post-shores is 750 tonnes-cm/rad in Figure 1 (Peng et al. 1998). As shown in Figure 3, the shores with pinned-pinned end (i.e. k_{sw}=0) are regarded as leaning columns. The shore with finite end stiffness (i.e. $k_{sw}\neq 0$) is defined as the strong shore.

3 ANALYSIS RESULTS AND DISCUSSION

3.1 End Stiffness of Shores

3.1.1 Wood post-shores

Figure 4 shows the end stiffness of wood post-shores of which the installation is based on the actual set-up of construction sites described above. The length of the shores H is 3.6 meters. The three curves in Figure 4 express the system critical loads for 1-shore, 4-shore, and 9-shore shoring systems. The symbol "×" shows the experimental results for the same configurations. The intersections of the horizontal lines passing through "×" and the theoretical curves represent the corresponding values of connection stiffness.

As seen in Figure 4, the end stiffness of the wood post-shore is about 100 tonnes-cm/rad for the 1-shore case. The end stiffness is about 50 tonnes-cm/rad for the 4-shore and 9-shore cases, respectively. Since the conditions of the 4-shore and 9-shore cases are closer to the actual construction site than the 1-shore case, the end stiffness 50 tonnes-cm/rad is more appropriate and used in the following sections.

In addition, the test result shows that the tested critical loads of shoring systems are lower than those calculated from an individual shore multiplied to the total numbers of shores in the shoring system (Peng et al. 1998). In design, each shore in the system is assumed to have the same load-carrying capacity. If the load capacity of the shoring system is calculated from these individual shores, it will be in the upper bound zone for the strength of the system. Thus, a modification factor is proposed to calibrate the system strength induced from the individual shores.

3.1.2 Metal post-shores

Figure 5 shows the end stiffness of metal post-shores of length 3.6 meters. There are two sets of lines in Figure 5. One is based on analysis of the 1-shore case and the other is from results of the 9-shore case. The stiffness, k_{sm}, is the joint stiffness of metal post-shores. As shown in Figure 5, the values k_{stb} and k_{sm} change from 0 to 300 tonnes-cm/rad and from 500 to 900 tonnes-cm/rad, respectively. The lines based on the 9-shore case are higher than those of the 1-shore case. Since the lines for the case of 1-shore are very close, the joint stiffness k_{sm} is not listed as in the case of 9-shore for clarity.

In the Figure, the symbol "×" on the y-axis shows the test results for the same numbers of shores. The averaged value is 2116 kgf for the 1-shore case and 16664 kgf for the 9-shore case. The end stiffness of the metal post-shore is about 120 tonnes-cm/rad for the 1-shore case and about 70 tonnes-cm/rad for the 9-shore case. Based on the same argument for wood post-shores, the end stiffness 70 tonnes-cm/rad is used for metal post-shores in this paper.

Figure 6(a) shows the deformed shape of a system of 9 metal post-shores before and after loading by the numerical analysis. The middle of each shore has the maximum lateral deformation. Figure 6(b) expresses the load-deflection curves of the shoring system. The asymptote to the curve is taken as the critical load of the shoring system.

3.2 Modification Factor and Simplified Design Process

3.2.1 Modification Factor

Based on test results (Peng et al. 1998), the critical load of the shoring system directly measured from the tests varies from 76% to 80% of the tested critical load of individual shores multiplied by the total numbers of shores. As described in the above section, the average value is about 80%. This reduced ratio is defined as the "Modification Factor", ξ_w. For conservatism in design, the factor of ξ_w=0.75 is used for wood post-shores in construction in Taiwan. For tested results of metal post-shores, the critical load of the shoring system is around 85% to 88% of the tested strength of individual shores multiplied by the total number of shores. For conservative design, this paper suggests a factor of ξ_s=0.80 for metal post-shores used in construction.

3.2.2 Suggested Design Process

Figure 7 shows numerical, design, and modified design values of wood post-shores based on load cases A and B. The "numerical values" are based on computer calculation, the "design values" are calculated by a simplified design formula, and the "modified design values" are equal to the design values times the above-modification factor.

There are four curves in Figure 7. Curves A and B are the design values based on the two load cases A and B. They are calculated by the average tested strength of individual shores multiplied by the shore number of their systems. These two curves can be considered as upper and lower bounds of the strength of shoring systems, respectively. For comparison, a solid curve with symbol (•) is obtained by computer calculation. A dash curve with symbol (Δ) shows modified design values. The dash curve is calculated from curve A by a multiplying modification factor ξ_w=0.75. As shown in Figure 7, the curve of the numerical values (•) is close to the curve of modified design values (Δ). Thus, this modified curve can be considered to replace a time-consuming computer analysis in design.

The proposed design formula of the critical loads of shoring systems is summarized as follows:

Case A : $P_{crt} = P_{cr} \times m \times n \times \xi$ (ξ_w for wood or ξ_s for metal)

Case B : $P_{crt} = P_{cr} \times (m-1) \times (n-1)$

where m and n = the shore number of both sides in the square shoring system; ξ="Modification Factor" of wood or metal post-shores; P_{cr}=the tested critical load of an individual shore; P_{crt}=the critical load of the entire shoring system.

Figure 8 shows numerical, design, and modified design values of metal post-shores by two load cases A and B in a similar procedure as wood post-shores. The trends of these four curves are very similar to those in Figure 7. The design system strength of metal post-shores can be calculated by considering Figures 5 and 8 based on the above design process.

3.3 Simplified 2-D Model

A simplified 2-D model is proposed to replace a complex 3-D model. Figure 9 expresses the analysis results of these two models by load case A. As shown in Figure 9, the analysis of the simplified 2-D model is very close to that of the 3-D model. Thus, the following analyses are based on this kind of 2-D model.

3.4 Leaning Column Effect and Suggestions of Shore Design

3.4.1 Wood post-shores

For simplicity, a strong shore with end stiffness k_{sw}=50 tonnes-cm/rad and leaning columns is considered in the analysis. The LeMessurier formula (LeMessurier 1977) can be written for effective length factor, $K=[(P_e/P_i)(\Sigma P/\Sigma P_{eK})]^{0.5}$, in which P_e is the Euler Load; P_i is the axial force in the column providing sideway resistance; ΣP is the total axial load on all columns in a story; ΣP_{eK} is the summation of the Euler buckling load of all columns in a story providing sidesway resistance, which can be evaluated using the effective length obtained from nomographs.

Figure 10 shows results for different numbers of bays by using the computer and by the LeMessurier formula. The stiffness of a horizontal beam is considered as rigid when compared with that of vertical shores based on actual construction conditions. This is due to the stiffness of the whole formwork being very strong when compared with each individual shore surveyed from actual construction sites. In computer analyses, the beam stiffness assumes 1000 times that of shores to simulate the rigidity. The end stiffness of wood post-shores is 50 tonnes-cm/rad as mentioned above. The height of shores is 360 cm and the distance between shores is 60 cm for load cases A and B based on the actual set-up in construction sites.

Figure 10 expresses the relationship between critical loads and the bay numbers of leaning columns in shoring systems. As shown in the figure, the solutions of the LeMessurier formula are slightly lower than computer solutions. This indicates that the LeMessurier's design formula can substitute for cumbersome numerical analyses by computers.

In the above set-up, when the number of strong shores is fixed, the critical load of shoring systems approaches a constant irrespective of the increase in the number of leaning columns. This result is valuable in verifying the safety of shoring systems in actual construction sites. During construction, workers need to realize whether the added shores are of contribution to the system stability or not. If only the leaning columns are added in the systems, the system critical loads will not increase. The shoring systems still have a potential danger. If the workers do not realize this behavior, it may lead to the collapse of shoring systems in construction sites.

3.4.2 Metal post-shores

To study the leaning column effect on a metal shoring system, the analysis process is similar to those for wood post-shores. In the analysis, the end stiffness of metal post-shores is taken as 70 tonnes-cm/rad based from the above derivation, and the stiffness of joints in metal post-shores is 750 tonnes-cm/rad based on tests (Peng et al. 1998).

Figure 11 shows the relationship between critical loads of shoring systems and the bay numbers of leaning columns for metal shoring system. In Figure 11, when the number of strong shores is fixed and the number of leaning columns increases, the critical load of shoring systems remains constant. This result resembles that for wood post-shores in Figure 10. In addition, the solutions derived from the LeMessurier formula are larger than those from numerical analyses. Due to the ignorance of the joint stiffness of metal shores, the LeMessurier formula predicts a much higher critical load. Designers should, therefore, be careful when using the LeMessurier formula for metal post-shores in design.

3.5 Quantities and Positions of Strong Shores

3.5.1 Wood Post-Shores

3.5.1.1 Numbers of Strong Shores

The effect of leaning columns is required to be considered when the bound of the system has sideway. This paper investigates the leaning column effect to shoring systems with various numbers of strong shores. In the analysis, the total number of wood post-shores is fixed at 30. Figure 12 shows the relationship between critical loads of wood shoring systems and the numbers of strong shores. There are two curves based on the LeMessurier formula and numerical analyses with load case A in the Figure. Figure 12 shows that these two curves are very close. This implies that the LeMessurier formula can be used to replace the complex numerical computing work in this condition for the shore design.

As shown in Figure 12, the critical loads of shoring systems P_{crt} increase linearly with the numbers of strong shores. This result is useful in strength design of shoring systems in construction. Based on this result, critical loads of other systems with various numbers of strong shores can be interpolated from the curves.

3.5.1.2 Ratios of Strong Shores

Figure 13 demonstrates the relationship between critical loads of shoring systems and the ratios of strong shores in various shoring systems. Three curves are based on various numbers of shores of 10, 20, and 30. As shown in Figure 13, these three curves increase linearly with the increase of the ratios of strong shores. In addition, the strength of shoring systems increases with the increase of the total number of shores when the ratios of strong shores are equal.

By interpolation, Figure 13 is applicable to different shore numbers. For example, if the total number of shores is 25 and the ratio of strong shores is 0.4, the following procedure can be used to determine the strength of the shoring system. From Figure 13, the linear curve for 25 shores can be found by interpolating between 20 shores and 30 shores by a dash line. With the ratio of strong shores equal to 0.4, the strength of 25 shoring system equal to 2160 kgf can be found on the y-axis.

From the above, Figure 13 can provide a quick prediction for the system strength of wood post-shores. Furthermore, based on assumptions in this paper, the system critical load of wood post-shores increases linearly with the increase of the number of strong shores. For the analysis and design of the shoring system, the critical loads of the entire shoring system can be found by multiplying the strength of an individual strong shore by the total numbers of strong shores. Figure 13 is very helpful in shore design.

3.5.1.3 Positions of Strong Shores

Based on leaning column effect, the change of positions of strong shores does not have an apparent influence on the critical load of the shoring system. A system of 10 shores with 3 strong shores is considered. Based from actual set-up on construction sites, the length of shores is 3.6 m and the distance between shores is 60 cm. The end stiffness of strong shores k_{sw} is 50 tonnes-cm/rad. The result, 651.4 kgf, shows that critical loads of the shoring systems almost do not change with the different positions of strong shores. This implies that the positions of strong shores are unimportant to the strength of a shoring system. For a one-layer shoring system in construction sites, workers should therefore be reminded of the importance of the number of strong shores, but not their locations.

3.5.2 Metal Post-Shores

Figure 14 shows the relationship between critical loads of a metal shoring system and the number of strong shores. In the Figure, the total number of shores is also equal to 30. As shown in the Figure, except for the larger discrepancy between two curves, the trend of the curves increases linearly with the increase of the number of strong shores. The numerical analyses have taken into account a joint stiffness of metal post-shores of 750 tonnes-cm/rad obtained from experimental tests (Peng et al. 1998). However, the rigid joint ($k_{sm}=\infty$) assumption is used in the calculation of the LeMessurier formula. This is the reason for a higher value computed by the LeMessurier formula when compared with numerical analysis results in Figure 14.

4. CONCLUSIONS

The following conclusions can be drawn from the studies.

1. For the assumptions based on actual construction sites, the end stiffness of 3.6 m shores should be taken as 50 tonnes-cm/rad for wood post-shores and 70 tonnes-cm/rad for metal post-shores for stability analyses.
2. If the shore design is based on an individual shore and the factor of safety is ignored, the modification factors of ξ_w = 0.75 for wood post-shores and ξ_s = 0.85 for metal post-shores are recommended in the system without the leaning column effect.
3. The system strength will not increase by an increase in number of leaning columns. In construction, the shores need to be distinguished between strong shores and leaning columns since leaning columns are useless for the strength of the shoring system. This is the main reason for collapse of falsework since workers do not normally realize this characteristic during construction.
4. The LeMessurier formula for wood post-shores can replace the complex numerical analysis. This approach is unconservative for metal post-shores since the joint stiffness is assumed rigid.
5. The critical loads of shoring systems increase linearly with the increase of the number of strong shores. In construction sites, ensuring individual shores as strong shores is a crucial point for improving the strength of the shoring system.
6. If the total number of shores and the ratio of strong shores are known, the critical load of the shoring system can be found by interpolation.
7. If the total number of shores is fixed, the critical loads of shoring systems are almost independent of the positions of strong shores.

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CONVERSION FACTORS

1 kgf (the weight of a mass of 1 kg) = 9.807 N
1 tonne = 9.807 kN (= 1000 kg)

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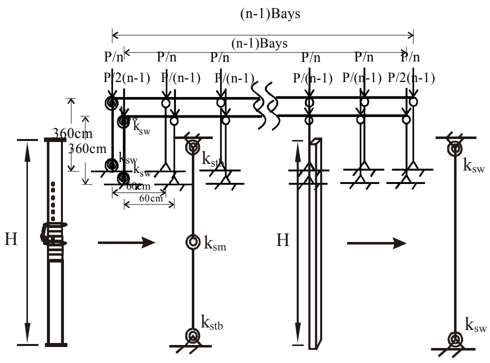


(Wood Post-Shore) (Metal Post-Shore)

Figure 1 Models of Wood and Metal Post-Shore

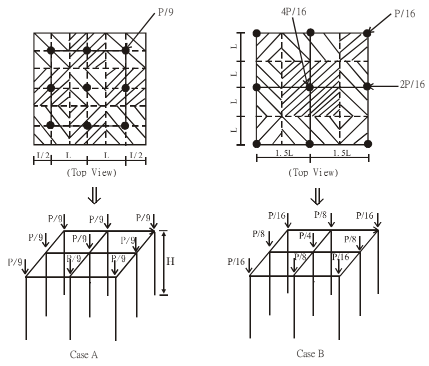


Figure 2 Arrangement of Load Case A and B

(Case A)

(Case B)

Figure 3 Analysis Models of Shoring Systems with Leaning Column Effect

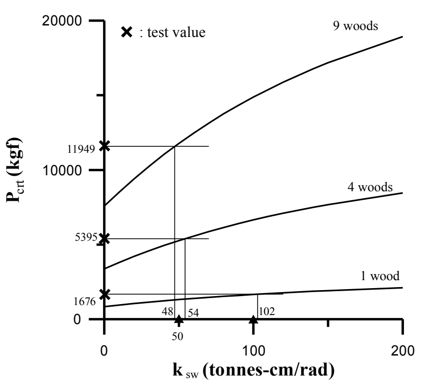


Figure 4 End Stiffness of Wood Post-Shores

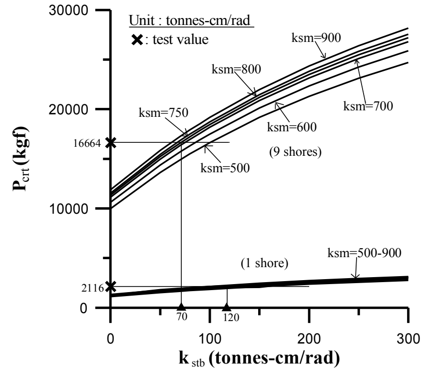
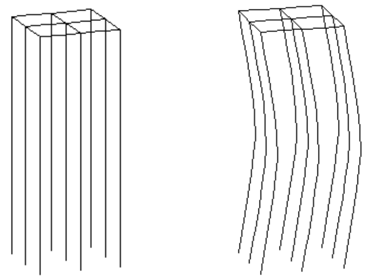


Figure 5 End Stiffness of Metal Post-Shores



(Before Loading) (After Loading)

Figure 6(a) Deformed Shape of 9 Metal Shoring System Before and After Loading

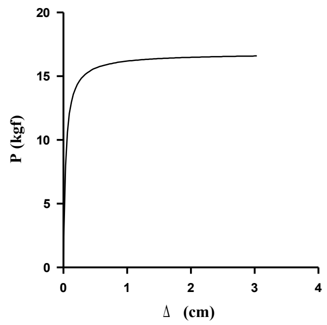


Figure 6(b) P-Δ Curve of 9 Metal Shoring System

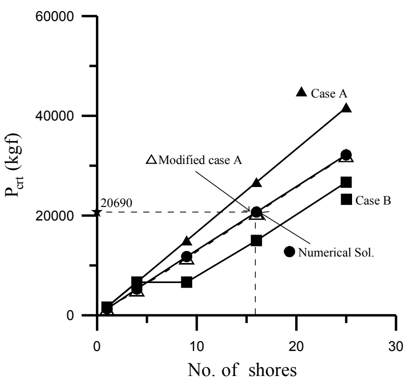


Figure 7 Critical Loads of Wood Shoring Systems

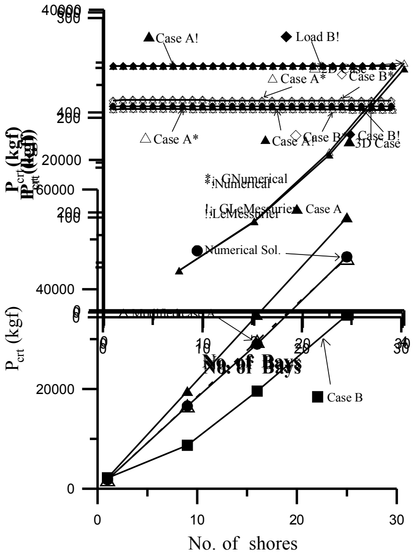


Figure 8 Critical Loads of Metal Shoring Systems

Figure 9 Comparison of 2-D and 3-D Models

Figure 10 Critical Loads of Wood Shoring Systems vs. Leaning Columns (1 Strong Shore)

Figure 11 Critical Loads of Metal Shoring Systems vs. Leaning Columns (1 Strong Shore)

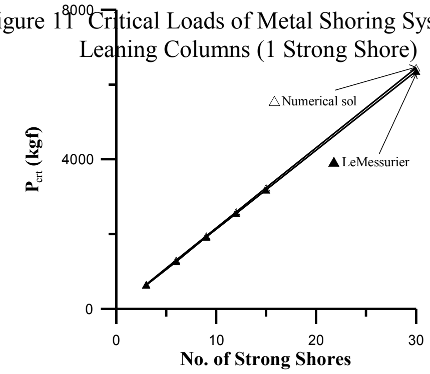


Figure 12 Critical Loads of Wood Shoring Systems vs. Strong Shores with Leaning Columns (30 shores)

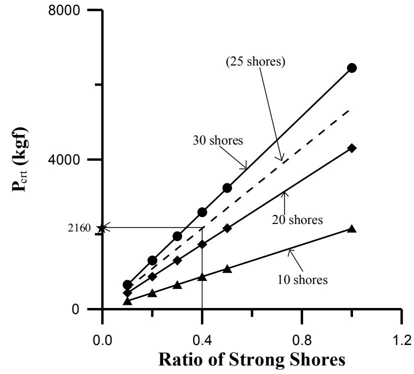


Figure 13 Critical Loads of Wood Shoring Systems vs. Ratios of Strong Shores with Leaning Columns

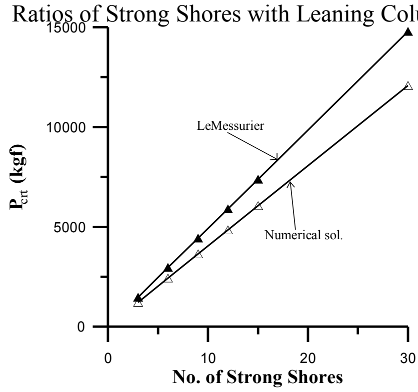


Figure 14 Critical Loads of Metal Shoring Systems vs. Strong Shores with Leaning Columns (30 shores)