Establishment of State-of-the-Practice for Scaffolding Platform for Slope Site Investigation Works

Submitted to
Hong Kong Construction Association

By

Albert T. Yeung
Department of Civil Engineering
University of Hong Kong
Pokfulam, Hong Kong

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Preface

Timber scaffolding have been commonly used in Hong Kong for the supporting of drilling rigs and other plants for site investigation works on slope surfaces and in areas of shallow water. The advantages of timber scaffolding over other types of temporary working platform are that it can provide relatively high bearing capacity as well as flexibility.

While the actual scaffolding process can vary depending on different site condition, all scaffoldings must be stably constructed in order to ensure the public are not endangered throughout the process.

We commissioned the University of Hong Kong to conduct a study and undertake the drafting of this document in the aim of standardizing the safe design of timber scaffolding. General guidelines and pointers are also given to the users for carrying out works on timber scaffolding.

Special thanks are due to all our HKCA Site Investigation Contractors Committee’s members for their practical advice on both the genesis and the particulars of this document. Without their contributions, this publication would not have been possible.

The purpose of this document is to provide practical guidance for person undertaking on the erection, use, alteration and dismantling of timber scaffolding. It is hoped that publication of this book will serve as a standard reference to the management teams at the forefront and to promote continuous improvement to the Industry.

Edward H.M. Cheng
Chairman of Site Investigation Contractors Committee, HKCA

March 2014
# Hong Kong Construction Association

## Site Investigation Contractors Committee  2013-2015

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Executive Summary

Temporary fir log scaffolding platforms are often required for slope site investigation works. It is contractually required by recent Government infrastructure construction contracts that the stability and structural adequacy of all these temporary works have to be certified by Independent Checking Engineers. However, there is no well-established procedure for the structural analysis of these scaffolding platforms built of fir logs. The dilemma poses an impasse to the construction industry. The University of Hong Kong was commissioned by the Hong Kong Construction Association to conduct this Study in an attempt to break through the impasse by a technically feasible and practical approach, so as to benefit the construction industry and the public.

A full-scale field evaluation of the engineering performance of a fir log scaffolding platform on sloping ground was conducted at the Kadoorie Research Institute of The University of Hong Kong. The design and construction of the platform was typical of those being used in slope site investigation works in Hong Kong. The live load imposed on the test platform was considerably heavier than a working platform. No instability or distress was observed on the test platform during the evaluation process, indicating the empirical rules of thumb adopted in the design and state-of-practice skill used in the construction of the platform by experienced and skilled scaffolders are satisfactory. Moreover, laboratory testing of fir logs, nylon ties, and the joints constructed by these materials; and numerical analyses of the fir log scaffolding platform were performed.

Further development on the structural analysis of fir log scaffolding platform is still required. However, on the basis of the engineering performance of the test platform, it is recommended that acceptance criteria of the design and construction of temporary fir log platform for slope site investigation works should be developed on the empirical rules of thumb for the design and the state-of-practice for the construction routinely adopted by experienced and skilled scaffolders, for the best benefits of the industry, the safety of construction workers, and public safety.

Albert T. Yeung, BSc(Eng)(Hon) MS PhD HKIE FICE FASCE RPE (Civil, Environmental, Geotechnical) CEng PE
Principal Investigator
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Introduction

1. It is contractually required by recent Government infrastructure construction contracts that the stability and structural adequacy of all temporary works to be constructed as part of these contracts have to be certified by Independent Checking Engineers. Scaffolding platforms built of fir logs for slope site investigation works are no exception. The policy has probably been implemented to further enhance the safety of construction workers and the public.

2. However, there is no established procedure for the structural analysis of these scaffolding platforms built of fir logs. The lack of analysis procedure poses a technical difficulty for any Independent Checking Engineer to make a quantitative assessment of the stability and structural conditions of the platform, not to mention to certify its structural and stability adequacy with reasonable professional skill and confidence.

3. The dilemma poses an impasse to the construction industry. Although these scaffolding platforms are absolutely necessary temporary works for site investigation works on slopes, they cannot be constructed without the certification of Independent Checking Engineers. Although these platforms have been used safely for decades in Hong Kong, Independent Checking Engineers do not have the tools or evaluation procedure to make the assessment and to certify the stability and structural adequacy of these platforms.

4. The University of Hong Kong was commissioned by the Hong Kong Construction Association to conduct this Study in an attempt to break through the impasse by a technically feasible and practical approach, so as to benefit the construction industry and the public. Ir Dr. Albert T. Yeung of the Department of Civil Engineering was appointed as the Principal Investigator of the Study.

Project Background

5. Temporary fir log scaffolding platforms, as shown in Figure 1, are often required for slope site investigation works. The platform is required to support the construction workers working on the platform, the drilling rig and associated equipment, the dynamic impacts induced by in-situ tests, in particular the SPT, and the reaction load induced on the platform during maneuvering of site investigation equipment and extraction of casing. In addition to dead load and live load, the platform has to resist other natural forces, such as wind load. In particular, the foundation of the platform can be scoured by rapid running water during heavy rainstorms.
6. Although the principles of design and construction are practically identical, these platforms can be of different configurations depending on slope geometry, site access, specific purposes, etc. Some of these different configurations are shown in Figure 2.

7. The structural members of the platform are fir logs of diameters ranging from 100 mm to 125 mm. As a natural material, the diameter of the fir log varies along its longitudinal axis. These fir logs are imported from outside Hong Kong and can be reused from project to project. The acceptability of these fir logs for re-use is assessed by visual inspection of scaffolders. In the current practice, these fir logs are tied together by nylon ties to construct the platform. A close-up of these connections is shown in Figure 3.

8. It should be noted that these fir logs were tied together by bamboo skin strips in the past, before the wide availability and application of nylon ties. The fir logs are held together by the friction between them at the connections and the tension in the ties. The tensile strength of the nylon tie is probably higher than that of the bamboo skin strip. Moreover, the stiffness of nylon ties is considerably lower than that of bamboo skin strips. As a result, the elongation of nylon ties is considerably larger than that of bamboo skin strips under the same tension. The friction between fir logs at the connection may thus be reduced. In the current practice, the nylon ties are re-tightened from time to time during the operation of the platform.
Figure 2. Different configurations of fir log scaffolding platforms

Figure 3. A close-up of the connection of fir logs by nylon ties
9. In the past, the art and skill of tying these bamboo skin strips or nylon ties are passed on from generation to generation through an apprentice system without an explicit standard of practice, rendering the assessment of the strength of these connections very difficult.

10. Moreover, there is no mathematical model that can represent the engineering behavior of the connection joint satisfactorily, not to mention the input parameters for the model. However, it should be noted that the engineering behavior of the connection joint is extremely complex, as its strength is derived from the friction between the fir logs and the tension in the nylon tie, and these two components are inter-related and inter-dependent. Coupling with the variation of engineering properties of fir logs, the stability and structural conditions of these fir log platforms are extremely difficult to be assessed by structural engineering calculations.

11. These platforms may be used for a brief period of time for site investigation works. However, they can also be used for a longer duration to support construction equipment for foundation and/or earth retaining structure construction.

12. These platforms have been used safely in the Hong Kong construction industry for decades. The builders of these platforms, i.e., scaffolders, are very experienced. There are empirical but not properly documented standard platform configurations for different site conditions adopted by experienced construction workers for quite some time. These empirical rules of thumb for design and skill for construction have been passed on from generation to generation. Moreover, these empirical designs and construction practices have been proven implicitly by experience to be adequate and fit for purpose.

The Problem

13. These platforms have been used safely in Hong Kong for decades. However, the Hong Kong SAR Government now requires all temporary works used in government contracts, including these fir log scaffolding platforms, to be certified by Independent Checking Engineers. It poses a genuine difficulty for the Independent Checking Engineer to perform a reasonable structural engineering analysis so as to evaluate the stability and structural adequacy of the platform.

14. The material properties are uncertain and these properties may deteriorate with time, in particular after a number of wetting and drying cycles. The efficiency of the connection is very difficult to assess, rendering it is very difficult to analyze the stability and structural conditions of the temporary platform. The reaction force acting on the platform can be significant during the extraction of casing upon completion of a borehole. During heavy rainstorms, the foundation may be subjected to scouring. Moreover, there may be different configurations of these platforms to suit different site conditions.

15. The Study was conducted to determine the stability of existing configurations of fir log platforms for slope site investigation works, and to develop a practical methodology to analyze the stability of different configurations of fir log platforms for slope site investigation works.
Historical Developments

16. Various construction techniques of these fir log scaffolding platforms, from choice of materials, tying of nylon ties, construction of foundation, to structural arrangement of fir logs, were passed on from generation to generation using an informal apprentice system in the past.

17. However, the scaffolding industry in Hong Kong is relatively small, and the population of scaffolders in Hong Kong is thus not very large. There is only a handful of construction companies specialized in scaffolding in Hong Kong. Therefore, it can be observed that these techniques do not vary significantly from scaffolder to scaffolder in Hong Kong. Moreover, the sources of materials are quite limited, rendering limited variability in the initial material properties of fir logs and nylon ties. Variability in material properties due to deterioration can be controlled implicitly by proper selection of materials by experienced scaffolders through visual inspection.

18. Since the establishment of Construction Industry Council Training Academy (CICTA), scaffolders have been trained through specifically designed training courses taught by qualified instructors. Moreover, scaffolders are required to pass specific trade tests to demonstrate that they possess the minimum standards of skills and to acquire recognized trade qualifications and status. Therefore, the experience in scaffolding platform construction can be passed on from generation to generation systematically, and trade practice and skill level of scaffolders are standardized to an acceptable extent these days.

Study Approach

19. Fir log scaffolding platforms have been used safely in Hong Kong for decades. Therefore, the experience of constructing of these safe platforms in the past is an important asset for any further development. The empirical rules of thumb for design and construction practice being used appear to be adequate in conjunction with the current skills of scaffolders in practice. However, there is a need to establish the adequacy of the current empirical design and construction practice scientifically and quantitatively, prior to further development of suitable analysis techniques or procedures, and to extend the current practice into new areas.

20. If the adequacy of the current empirical design and construction practice can be established, the study approach should be formulated to minimize any undue disturbance to the current practice of scaffolders and to avoid any unnecessary mistakes caused by abrupt changes in practice. It is not necessary to re-train and re-test all the existing skilled scaffolders, or to change their mindset and the skills they acquired through conventional training and decades of practice. More importantly, it does not require re-establishing the confidence of end-users of these platforms on the stability and structural adequacy of these platforms. The current training courses and trade skill tests being offered by CICTA can be used continuously with minimal modifications. Otherwise, it would take quite some time to re-train and re-certify the instructors, and to modify the course contents, so as to accommodate any drastic changes. Moreover, any disruption to the construction industry is also minimized, as there would not be any time gap required for re-training and re-testing of all the existing skilled scaffolders in the industry, and for re-establishment of confidence of the end-users of these platforms.
21. The most practical approach was thus adopted in this Study. A full-scale field evaluation of the engineering performance of an existing platform configuration was conducted at a test site of the Kadoorie Research Institute of The University of Hong Kong in Shek Kong, New Territories.

22. Laboratory tests were performed on nylon ties, fir logs and connection joints to develop a better understanding of the engineering behavior of these structural components of the fir log scaffolding platform.

**The Field Test**

23. The test site at the Kadoorie Research Institute of The University of Hong Kong was selected for security purposes. It is within the premises of The University of Hong Kong, so that the test would not be disturbed by trespassers. It was also isolated from public access for safety reasons. Moreover, the site has been used for research in compaction of slopes, performance of soil nails, etc., and the research team of The University of Hong Kong is familiar with the conditions and logistic requirements of the site. Supplies of electricity, water, storage space, etc. necessary to support the Study were readily available. Moreover, site access was not difficult.

24. A slope within the Kadoorie Research Institute of The University of Hong Kong was selected as the test site for the construction of a fir log scaffolding platform to simulate most sloping sites for site investigation works that would require the construction of temporary fir log scaffolding platforms.

25. The platform was solely designed and constructed by qualified scaffolders to suit site conditions according to their experience, state-of-the-practice and judgment, with a view to evaluating the adequacy of the current empirical design and construction practice. Moreover, the design was endorsed by the Site Investigation Contractors Committee of the Hong Kong Construction Association. The design sketches are given in Appendix I. However, modifications were made on site to suit site conditions. The required safety features, such as kick boards and protective meshes around the platform edges, were also constructed to completely replicate a fir log scaffolding platform in real-life practice. More importantly, the practice is within the technical know-how of most experienced and skilled scaffolders in Hong Kong.

26. The working area of the platform was slightly larger than 15 m². The foundation was constructed in a typical manner. A typical connection was used to connect the platform to its foundation. A photograph of the test platform is shown in Figure 4. It can be observed that the corner of the platform on the right hand side was higher from the ground than that on the left hand side due to the sloping ground.
27. Ten 1 m$^3$-water containers were installed on the platform as shown in Figure 5 so that a total of 10 tonnes of simulated live load could be imposed on and removed from the platform sequentially.

28. The live load acting on a typical platform for site investigation works was estimated to be 6 tonnes. The live load of 10 tonnes imposed on the test platform was considerably higher than the live load that the platform would be designed to support. If the platform could support the 10-tonne live load safely, there would be
considerable safety margin and redundancy during the normal operation of the platform.

29. Linear variable differential transducers (LVDTs) and strain gauges were installed on selected fir logs of the platform as shown in Figures 6 and 7 to measure displacements and strains of these fir logs of the test platform under loading.

![Figure 6. Instrumentation on the test platform](image1.png)

30. It can be observed in Figure 6 that the LVDTs were installed on an independent frame built of steel angles completely isolated from the test platform, so that the effects of

![Figure 7. Instrumentation on the test platform](image2.png)
the instrumentation on the engineering performance of the test platform was minimal, if any. Moreover, it can be observed a small Plexiglas stud was glued on the fir log to seat the LVDT so that it would not slip as a result of the roundness of the fir log.

31. It can be observed from the number of connecting wires shown in Figure 7 the extensiveness of instrumentation.

32. The full-scale field test of the platform was conducted on 4 January 2011. It was a windy day with a heavy downpour. Although the inclement weather imposed some inconvenience to the testing operation, it provided an excellent opportunity to evaluate the stability and structural adequacy of the platform, and to identify any site operation problems of the platform under severe weather conditions.

33. All the LVDTs and strain gauges installed were connected to a multi-channel data logger as shown in Figure 8. Initial readings were taken and the data logger was set to collect data by sweeping the channels at regular time intervals. Moreover, hard copies of the data collected over time were printed out at regular time intervals to guard against any unexpected malfunctioning of the data logger and/or accidental cutoff of power supply, etc.

34. The test platform was loaded by filling the water tanks manually one by one as shown in Figure 9 from the center of the test platform outwards. The loading sequence was adopted to best simulate the operation of the platform, as most site investigation works are normally performed at the center of the temporary fir log scaffolding platform.

Figure 8. The multi-channel data logger
35. It can be observed from the strains measured at different fir logs that the vertical deformation induced by the imposed load was quite localized, i.e., the load imposed at a location was supported by vertical structural members in the vicinity of the imposed load. Lateral spreading of the load to other vertical structural members by horizontal structural members was quite limited.

36. The lateral displacement of the platform deck was generally in the downward direction of the slope. Moreover, it was in the direction towards the corner at the highest vertical distance from the ground. The displacements were so large at some locations that the LVDTs moved almost out of the Plexiglas seating stud as shown in Figure 10. At some locations, we had to reset the LVDT so as to continue our vertical displacement measurements. It can also be observed in Figure 10 that the platform moved diagonally towards the corner at the highest distance from the ground in the downward direction of the slope. The original location of the LVDT was at approximately the center of the Plexiglas seating stud. The lateral displacement was estimated to be more than 10 mm by visual inspection.

37. There were LVDTs installed to measure the lateral displacement of some vertical fir logs of the platform as shown in Figure 11. However, the lateral displacements so measured were considerably less than those observed on the Plexiglas seating studs installed underneath the deck, indicating that the deck was moving laterally relative to the foundation of the platform.

38. The phenomenon is probably caused by the non-symmetric configuration of the platform. Due to the non-uniform topography of the site, the two corners of the platform in the downward direction of the slope were not at equal height from the
ground. As a result, when vertical loads were imposed on the platform, a lateral force was induced in the direction towards the corner at the highest distance from the ground. The lateral force induced bending of the vertical fir logs supporting the deck and tension in the nylon ties typing the fir logs together at the connections. Bending of the vertical fir logs induced swaying of the platform. Stretching of nylon ties at the connections of the platform deck led to slight relative movement of the fir logs at the connections, resulting in considerably larger lateral displacements of the platform deck when vertical loads were imposed on the platform.

![Figure 10. Lateral displacement of the platform deck](image)

![Figure 11. Measurement of the lateral displacement of vertical structural members by LVDT](image)
39. Although the lateral displacements at the platform deck were considerably larger than those measured at the vertical fir logs near the foundation, they do not pose any stability or structural adequacy problem of the fir log scaffolding platform.

40. The vertical displacements measured at the vertical fir logs were acceptable, in the order of 20 mm; indicating the empirical structural design of the platform is adequate in terms of the structural capacity of the platform. Moreover, the results also indicate that the empirical design of the foundation system was adequate as settlement of the platform was acceptable for the temporary structure. It should be noted that the field-scale evaluation was performed during a heavy rainstorm. Some of the supporting soil around the foundation members was scoured. Therefore, the performance of the test platform also demonstrated there was sufficient safety margin against scouring of the foundation.

41. The lateral displacements measured at the vertical fir logs were also very small, in the order of a few millimeters; indicating the empirical design of the bracing system is also adequate and very conservative.

42. The loads imposed on the platform were unloaded in reversed sequence by draining the water tanks as shown in Figure 12.

![Figure 12. Draining of water tanks to unload the platform](image)

43. During the unloading of the platform, the recovery of vertical displacements of the platform was very small; indicating most of the vertical displacements were contributed by the inelastic settlement of the platform foundation. As the penetration of the foundation into the ground is very small, the bearing capacity of the foundation is thus primarily derived from the tip resistance of the foundation, resulting in the development of inelastic settlement upon loading.


**Laboratory Tests**

44. Laboratory tests were conducted on nylon ties, fir logs and typical types of connection joints. The test samples were provided by the Hong Kong Construction Association. The nylon ties and fir logs were assessed by skilled scaffolders through visual inspection to be suitable for the construction of platforms for slope site investigation works. Different types of connection joints were constructed by different skilled scaffolders using the state-of-the-practice for testing.

**Properties of nylon ties**

45. Samples of nylon ties routinely used in the construction of platforms on site were supplied by the Hong Kong Construction Association for evaluation. The properties of these nylon string samples were evaluated in the Strength of Materials Laboratory of the Department of Civil Engineering of The University of Hong Kong.

46. The width and the thickness of the nylon tie were measured accurately. It can be observed from the results of the measurements that the width of the nylon tie varies between 5.59 mm to 6.60 mm, with a mean of 6.05 mm and a standard deviation of 0.38 mm. The thickness of the nylon tie varies between 0.76 mm to 0.99 mm, with a mean of 0.85 mm and a standard deviation of 0.072 mm.

47. Statistical analyses on the width of the nylon tie were performed, with a view to identify a suitable probability distribution for future analyses. The probability plots using a uniform distribution, a normal distribution and lognormal distribution are presented in Figures 13, 14 and 15, respectively.

48. It can be observed in these figures that none of the assumed distributions can represent the variation of nylon tie width well, as the data deviate considerably from the best-fit line. Moreover sampling may be required to establish a better probability distribution of nylon tie width, if necessary.

![Figure 13. Probability plot of nylon tie width assuming a uniform distribution](image-url)
Figure 14. Probability plot of nylon tie width assuming a normal distribution

Figure 15. Probability plot of nylon tie width assuming a lognormal distribution

49. Statistical analyses on the thickness of the nylon tie were similarly performed. The probability plots using a uniform distribution, a normal distribution and lognormal distribution are presented in Figures 16, 17 and 18, respectively.

50. It can be observed in these figures that the variation of nylon tie thickness fits all these assumed distributions reasonably well for practical purposes, while the uniform distribution appears to be slightly better than the other two distributions.
51. It can be envisaged that the nylon ties are manufactured in a two-step process. A nylon sheet is produced by a protrusion process first. It is subsequently cut into ties. As a result, the width of the nylon tie is much more random, as it is heavily dependent on the quality control of the cutting process. In contrary, the protrusion process is a much better controlled manufacturing process, resulting in a more systematic distribution of the thickness of the nylon tie.
The stress-strain characteristics of five specimens of nylon ties were measured in the Strength of Materials Laboratory of the Department of Civil Engineering of The University of Hong Kong. The width and thickness of each specimen were measured many times at different locations along its length to obtain the average values to determine the cross-sectional area of the specimen for calculation of the applied stress. The gauge length of each specimen was measured between the grips after it had been mounted on the testing machine as shown in Figure 19 using a minimum seating load. The dimensions of the test specimens are tabulated in Table 1. The applied load and the resulting elongation of the specimen were recorded by the testing machine automatically. The stress-strain characteristics of these specimens are shown in Figures 20 to 24. All these figures are plotted in the same scales for easy comparison.

Table 1. Dimensions of test specimens of nylon ties

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Average Width (mm)</th>
<th>Average thickness (mm)</th>
<th>Gauge length (mm)</th>
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<td>(3)</td>
<td>(4)</td>
</tr>
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<tr>
<td>5</td>
<td>5.64</td>
<td>0.79</td>
<td>200.0</td>
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</tbody>
</table>
Figure 19. Testing machine for nylon ties

Figure 20. Stress-strain characteristics of nylon tie specimen 1
Figure 21. Stress-strain characteristics of nylon tie specimen 2

Figure 22. Stress-strain characteristics of nylon tie specimen 3

53. The gripping of the specimen during the tensile test is not an easy task, as the nylon tie is quite slippery. Specimen slippage occurred from time to time during the test. When the nylon tie was under tension, its cross-sectional area reduced during the test as a result of Poisson effect. The grips holding the specimen had to be re-tightened from time to time to continue the test. However, the specimen could not be over-tightened at the onset of the test, as over-tightening of the grips would shear the cross-section at the connection point and create a weak cross-section in the specimen, resulting in a premature failure at the shear-weakened cross-section.
It can be observed in Figure 20 that specimen slippage occurred at point A, as the stress decreased with increase in strain. The slipping was noticed at point B and the specimen was re-tightened as indicated by the jagged stress-strain curve. Similarly, it can be observed that the specimen was re-tightened at points C and D. The specimen exhibited a slight strain softening after an ultimate tensile stress of 230 MPa had been reached. A sudden slipping occurred after point D but the specimen was caught by the grips shortly afterwards. Finally, the specimen failed in a sudden brittle mode at an ultimate strain of approximately 30%. The ultimate strain can only be estimated as the specimen slippage has to be deduced from the measured elongation.

Figure 23. Stress-strain characteristics of nylon tie specimen 4

Figure 24. Stress-strain characteristics of nylon tie specimen 5
55. On the basis of the experience gained in the testing of specimen 1, specimen 2 was re-tightened at point A as shown in Figure 21. However, specimen slippage still occurred at point B. The specimen was re-tightened at points C, D and E. The specimen exhibited a slight strain softening after an ultimate tensile stress of 200 MPa had been reached. Finally, the specimen failed in a sudden brittle mode at the ultimate strain of approximately 40%. The ultimate strain can only be estimated as the specimen slippage has to be deduced from the measured elongation.

56. During the testing of specimen 3, the specimen was re-tightened at point A as shown in Figure 22. However, specimen slippage still occurred at point B. The specimen was re-tightened at points B and C. The specimen exhibited a slight strain softening after an ultimate tensile stress of 200 MPa had been reached. Finally, the specimen failed in a sudden brittle mode at an ultimate strain of approximately 48%. The ultimate strain can only be estimated as the specimen slippage has to be deduced from the measured elongation.

57. Specimen 4 was re-tightened at points A, B and C as shown in Figure 23. It can be observed that there was no specimen slippage during the test. The specimen exhibited a slight strain softening after an ultimate tensile peak stress of 230 MPa had been reached. Finally, the specimen failed in a sudden brittle mode at an ultimate strain of 41%.

58. Specimen 5 was re-tightened at only point A as shown in Figure 23. It can be observed that there was no specimen slippage during the test. The specimen exhibited a slight strain softening after an ultimate tensile stress of 240 MPa had been reached. Finally, the specimen failed in a sudden brittle mode at an ultimate strain of 35%.

59. When the specimen fails in tension, it suddenly shatters into broken fibers as shown in Figure 25. The sudden brittle failure mode of the material can be attributed to the failure phenomenon observed.

60. Overall, it can be observed from the tensile test results of these specimens that the stress-strain relationship of the nylon material used to make scaffolding ties is non-linear. The initial tangential modulus is very high. The ultimate tensile stress of the material is higher than 200 MPa. The secant modulus at the ultimate tensile stress is higher than 800 MPa. The material exhibits a slight strain softening after the ultimate tensile stress has been reached. The material exhibits significant ductility prior to failure. However, the nylon tie material also fails in tension in a sudden brittle mode at an ultimate strain of higher than 35%.

**Engineering properties of fir logs**

61. Samples of fir logs were provided by the Hong Kong Construction Association to the Material Testing Laboratory of the Department of Civil Engineering of The University of Hong Kong for evaluation of their engineering properties. These samples were considered to be typical and suitable for the construction of temporary platforms for slope site investigation works.
As the fir log samples were variable in length and appeared to be heterogeneous in engineering properties by visual inspection, it was decided to evaluate their engineering properties in specimen size as large as possible, as any specimen preparation process may generate bias of the engineering properties measured through the specimen selection process.

Axial loading of the specimen is impractical as the specimen has to be cut in limited lengths and the ends of the specimen has to be capped to provide horizontal surfaces to apply the axial load vertically. Therefore, it was decided to pin-support the specimen at two ends and to apply a point load perpendicular to the longitudinal axis of the specimen at the center, so as to determine the flexural strength of the fir log in the experimental setup shown in Figure 26.

As the cross-section of the fir log specimen is not truly circular, the specimen may rotate during the loading process. Therefore, a Plexglas seating stud was glued to the specimen to accommodate two LVDT transducers to measure the deflection of the specimen under the point load as shown in Figure 27. Moreover, two strain gauges were glued on the underside of the specimen to measure the strain induced by the point load as shown in Figure 28. It can also be observed in Figure 28 that two nails were installed to support the Plexglas stud.

The point load was applied vertically by a freely supported semi-spherical loader as shown in Figures 26 and 28. The smooth surface of the semi-spherical loader can also avoid unnecessary stress concentration on the specimen. The applied load, the deflections and the strains measured by a load cell, two LVDT transducers and two strain gauges, respectively were recorded simultaneously by a data logger at regular intervals.
Figure 26. Experimental setup for flexural strength measurements of fir logs

Figure 27. Two LVDT transducers installed to measure deflection of the fir log specimen under load
Figure 28. Strain gauges installed on the circumference of the fir log specimen

The diameter of each specimen was measured ten times at ten different locations along the longitudinal axis of the specimen. The distance between supports was set as long as the length of the fir log allowed. The distance between supports and the average diameter of the specimen are tabulated in Table 2 and indicated on the respective figures. The load-strain and deflection-load curves of nine specimens are presented in Figures 29 to 46.

Table 2. Average diameter and distance between supports of fir log specimens

<table>
<thead>
<tr>
<th>Specimen No. (1)</th>
<th>Average diameter (mm) (2)</th>
<th>Distance between supports (mm) (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>116.4</td>
<td>1,500</td>
</tr>
<tr>
<td>2</td>
<td>120.1</td>
<td>1,500</td>
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<td>112.9</td>
<td>900</td>
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<td>4</td>
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</tr>
<tr>
<td>9</td>
<td>112.2</td>
<td>1,300</td>
</tr>
</tbody>
</table>
It can be observed in these figures that the variation of strain and deflection were linear at the initial stage and became non-linear as the applied load was increased. Best-fit-lines passing through the origin were thus constructed for the experimental data in the elastic sections of these curves to define the slopes of the elastic section of these curves for further analyses.

Figure 29. Load-strain curve of fir log specimen 1

Figure 30. Deflection-load curve of fir log specimen 1
Figure 31. Load-strain curve of fir log specimen 2

Figure 32. Deflection-load curve of fir log specimen 2
Figure 33. Load-strain curve of fir log specimen 3

Figure 34. Deflection-load curve of fir log specimen 3
Figure 35. Load-strain curve of fir log specimen 4

Figure 36. Deflection-load curve of fir log specimen 4
Figure 37. Load-strain curve of fir log specimen 5

Figure 38. Deflection-load curve of fir log specimen 5
Figure 39. Load-strain curve of fir log specimen 6

Figure 40. Deflection-load curve of fir log specimen 6
Figure 41. Load-strain curve of fir log specimen 7

Figure 42. Deflection-load curve of fir log specimen 7
Figure 43. Load-strain curve of fir log specimen 8

Figure 44. Deflection-load curve of fir log specimen 8
It can be observed in Figure 47 that the semi-spherical loader deformed and penetrated the fir log extensively during the flexural strength measurement. Moreover, cracks developed and propagated along the longitudinal direction of the specimen at failure, indicating the failure mode of the fir log is extremely complicated.
69. The maximum deflection of a simply supported beam under a point load $P$ at the center is given by

$$\delta = \frac{PL^3}{48EI} \quad (1)$$

where $\delta =$ maximum deflection at the center (mm); $P =$ applied load (kN); $E =$ Young's modulus of the material (kN/mm²); and $I =$ moment of inertia of the cross-section about the neutral axis (mm⁴).

70. Therefore, the slope of the deflection-load curve gives $L^3/(48EI)$. Using the experimental data presented in Figures 30, 32, 34, 36, 38, 40, 42, 44 and 46, the Young's moduli of the fir log specimens computed are tabulated in Table 3. The neutral axis of the cross-section is assumed to be the diametrical axis of the circular cross-section. The assumption is considered to be reasonable as any variation of engineering properties of the fir log is assumed to be axisymmetric.

71. It should be noted the calculations tabulated in Table 3 are performed on the assumption that the deflection is primarily caused by bending.

72. The relationship between the strain on the circumference of the fir log underneath the applied load at the center of the fir log, and the applied load is given by

$$P = \frac{AE\varepsilon}{rL} \quad (2)$$

where $\varepsilon =$ strain on the fir log circumference underneath the applied load; and $r =$ radius of the fir log.
Table 3. Young's moduli of fir logs from deflection measurements

<table>
<thead>
<tr>
<th>Specimen No. (1)</th>
<th>D (mm) (2)</th>
<th>L (mm) (3)</th>
<th>I (mm⁴) (4)</th>
<th>Slope (mm/kN) (5)</th>
<th>E (kN/mm²) (6)</th>
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</table>

Therefore, slope of the load-strain curve gives 4EI/(rL). Using the experimental data presented in Figures 29, 31, 33, 35, 37, 39, 41, 43 and 45, the Young's moduli of specimens computed are tabulated in Table 4.

Table 4. Young's moduli of fir logs from strain measurements

<table>
<thead>
<tr>
<th>Specimen No. (1)</th>
<th>D (mm) (2)</th>
<th>L (mm) (3)</th>
<th>I (mm⁴) (4)</th>
<th>Slope (kN) (5)</th>
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Both calculations tabulated in Tables 3 and 4 are based on the deflection of beam theory. If the assumptions of theory are valid for fir logs, the Young's moduli so calculated should be identical. A comparison of the results is tabulated in Table 5.

It can be observed in Table 5 that the Young's moduli deduced from circumferential strain measurements are considerably and consistently larger than those deduced from deflection measurements.

In the deflection of beam theory, the bending stresses appear to be of primary concern for beams in bending. However, shear stresses do exist in beams when transverse loads other than pure bending moments are applied. These shear stresses are of particular concern when the longitudinal shear strength of materials is low compared to the longitudinal tensile or compressive strength, such as in fir logs with the grain running along the length of the log.
Table 5. A comparison of Young's moduli of fir logs from strain and deflection measurements

<table>
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<tr>
<th>Specimen No. (1)</th>
<th>D (mm) (2)</th>
<th>L (mm) (3)</th>
<th>I (mm⁴) (4)</th>
<th>E¹ (kN/mm²) (5)</th>
<th>E² (kN/mm²) (6)</th>
<th>Ratio (5)/(6) (7)</th>
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<tr>
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<td>1,300</td>
<td>7,779,314</td>
<td>11.229</td>
<td>5.003</td>
<td>2.245</td>
</tr>
</tbody>
</table>

Notes: ¹Values deduced from circumferential strain measurements. ²Values deduced from deflection measurements.

77. The effect of shear stresses can be visualized if one considers a fir log is made up of flat boards stacked on top of one another without being fastened together and then loaded in a direction normal to the surface of the boards. The resulting deformation will appear somewhat like a deck of cards when it is bent. The resulting deformation will distort the log such that some of the assumptions made to develop the deflection of beam theory, for example, plane sections remaining plane, not valid.

78. Therefore, the deflection of the fir log is considerably larger than that induced by pure bending, resulting in a smaller rigidity calculated. Moreover, the Young's modulus may not be uniform throughout the fir log. Therefore, circumferential strains measured may not agree with those given by the deflection of beam theory.

79. An attempt was made to use the Schmidt hammer test to measure the hardness of the fir log as an indication of its strength. However, the results indicate that distribution of hardness on the fir log surface was quite scattered, and the hardness measured was heavily dependent on the location chosen to perform the test.

**Engineering behavior of the connection joints**

80. Connection joints are fabricated by scaffolders on site. These connection joints are made by tying fir logs together by nylon ties by hand. Therefore, the strength of the connection joint is derived from a combination of the friction between the fir logs and the tension in the nylon ties. The friction depends on the texture and surface conditions of the fir logs, and the normal reaction between the fir logs induced by the tension in the nylon ties. Therefore, these two components are inter-related and inter-dependent.

81. Two typical types of connection joints have been identified from typical construction details of temporary platform for slope site investigation works. Having considered the typical details of connection joints constructed on site and possibilities of testing
arrangements in the laboratory, two test configurations of connection joints as shown in Figure 48 were adopted: (1) cross connection joints; and (2) longitudinal connection joints. A cross joint connects a horizontal fir log member to a vertical member by a nylon tie, while a longitudinal joint connects two vertical members together by two nylon ties.

(a) Cross joints   
(b) Longitudinal joint

Figure 48. Configurations of connection joints adopted for laboratory testing

82. Three frames consisting of 4 cross joints each and three longitudinal joints were fabricated by different scaffolders using typical nylon ties. No specific instructions except the dimensions as shown in Figure 48 were given to the scaffolders. Therefore, the scaffolders would tie the fir logs together using their typical state-of-the-practice method. Afterwards, these connection joints were delivered to the Material Testing Laboratory of the Department of Civil Engineering of The University of Hong Kong for evaluation of their engineering properties. The connection joints delivered are shown in Figures 49 and 50. Therefore, there were a total of 12 cross joints and 3 longitudinal joints for testing in the laboratory. After delivery, every fir log member and every connection joint were numbered as shown in the figures. Fir log members that were too long were cut to fit the headroom of the testing machine.

83. A detailed observation of the each connection joints reveals that every joint was fabricated by warping the nylon tie around the fir logs eight times, regardless it was a cross joint or a longitudinal joint. It appears that the standard trade practice of constructing a joint follows three steps: (1) warping the fir logs eight times by a nylon tie; (2) twisting the ends of the nylon tie together; and (3) shuffling the twisted ends into the warped nylon tie for anchorage by the tension of the nylon tie as shown in Figures 51 and 52. It was observed that every connection joint submitted was constructed following the exact same procedure.
Figure 49. A cross connection joint

Figure 50. A longitudinal connection joint
A pair of cross joints was load tested simultaneously as it was very difficult to apply load to a single cross joint. A vertical load was applied at the center of the horizontal fir log through a freely-supported semi-spherical loader to impose the load on the two cross joints as shown in Figure 53. The frame was mounted on the testing machine so that the horizontal fir log was leveled. The tips of the vertical fir logs were fixed as shown in Figure 54. However, it should be noted that the reactions from the tips of the vertical fir log and the applied load are offset by a diameter of the fir log. Therefore, there was an eccentricity of the load applied to the cross joints.
Figure 53. Experimental setup for testing of cross joint

Figure 54. Fixing of the feet of the vertical fir log for testing
85. It should be noted that three were 3 frames consisting of cross joints. Cross joints 1 to 4 were on frame 1, cross joints 5 to 8 were on frame 2, and cross joints 9 to 12 were on frame 3. All the four cross joints on a single frame were probably constructed by a single scalforder.

86. The force acting on the horizontal fir log and the displacement of the semi-spherical loader were recorded simultaneously by the testing machine at regular intervals. The force-displacement curves of the six tests on cross joints in pairs are shown in Figures 55 to 60. All these figures are plotted in the same scales for easy comparison.

**Figure 55. Force-displacement curve of cross joints 1 and 2**

**Figure 56. Force-displacement curve of cross joints 3 and 4**
Figure 57. Force-displacement curve of cross joints 5 and 6

Figure 58. Force-displacement curve of cross joints 7 and 8
It can be observed from these figures that the force-displacement curves were linear initially, indicating the resistance to the applied load was derived from the friction between the fir logs. Once the friction had been fully mobilized, further resistance was provided by the tension in the nylon tie. However, the nylon tie could slip on the vertical fir log, rendering the resistance to applied load so provided not consistent. Slipping of the nylon tie with increase in applied load was observed during the test as shown in Figure 61. The lines indicated the position of the nylon tie and the numbers depicted the corresponding applied load.
88. It can be observed from these figures that all pairs of cross joints can support an applied load of more than 4 kN. Assuming the two cross joints can share the applied load equally, each joint can thus support more than 2 kN which is considerably more than the weight of a construction worker.

89. It can also be observed from the characteristics of these load-displacement curves that workmanship plays a very important role in the performance of these cross joints. It is quite obvious that the workmanship of the scalfolder who constructed frame 3 is better than that of the scalfolder who constructed frame 2, which in turn is better than that of the scalfolder who constructed frame 1.

90. It is also interesting to note that the horizontal fir logs failed before the failure of cross joints 9 and 10, and cross joints 11 and 12 as shown in Figures 62 and 63, respectively. It is quite surprising that two cross joints are stronger than the flexural strength of fir log.

91. As shown in Figures 59 and 60, these horizontal fir logs failed at the applied load of approximately 14 kN, indicating the cross joints were extremely strong when the workmanship was good, as cross joints 9, 10, 11 and 12 were constructed by the same scalfolder.
Figure 62. Failure of the horizontal fir log prior to failure of cross joints 9 and 10

Figure 63. Failure of the horizontal fir log prior to failure of cross joints 11 and 12
The longitudinal joints were similarly load tested. The joint was first mounted on the testing machine as shown in Figure 64. The tip of the lower vertical fir log was fixed using a clamp. The vertical load was applied to the upper vertical fir log through a freely supported universal joint loader as shown in Figure 65 to transfer the applied load to the longitudinal joint vertically.

Figure 64. Experimental setup for testing of longitudinal joint
93. The force acting on the upper vertical fir log and the displacement of the universal joint loader were recorded simultaneously by the testing machine at regular intervals. The force-displacement curves of the three tests on three longitudinal joints are shown in Figures 66 to 68. All these figures are plotted in the same scales for easy comparison.

Figure 66. Force-displacement curve of longitudinal joint 1
It can be observed from these figures that the displacement increased practically linearly with the applied force after some initial slack of the testing system had been removed. The applied force reached the peak value while the displacement was approximately 50 mm when the friction between the fir logs was fully mobilized. Afterwards, considerable relative sliding displacement occurred between the fir logs without any increase in the load resistance of the longitudinal joint. The relative displacement was measured as a function of applied load by a level as shown in Figure 69. Typical results are shown in Figure 70.
Figure 69. Measurement of relative Displacement of the fir logs

Figure 70. Relative Displacement of the fir logs of longitudinal joint 1
The fir log on the left shown in Figure 70 was the upper fir log of longitudinal joint 1. The two horizontal lines labeled by the number 2.9 as marked on the two fir logs were at the same level when the applied load was 2.9 kN. It can be observed that the upper fir log was moving downward relative to the lower fir log. The slanted lines indicate the positions of the nylon ties as a function of applied load. Although there were considerable relative displacements between the fir logs, there was no drastic or brittle failure of the longitudinal joint. In some cases, the test had to be terminated as the downward movement of the upper fir log became excessive and the tip of the upper fir log hit the bottom of the testing machine as shown in Figure 71. The tremendous elongation of the nylon tie can also be observed in Figure 71.

Figure 71. Termination of a test as the lower fir log hit the bottom

The structural adequacy of the different connection joints is demonstrated by the loading test results. When the workmanship is good, the connection joints can possibly be stronger than the fir log.

However, sliding of the nylon ties on the fir log under load can significantly increase the displacement of the connection joints. When the displacement becomes excessive, it may affect the normal operation of the fir log scaffolding platform.

Numerical Analysis

Structural analyses of the test platform were performed using the software 3D3S developed by Tongji University of Shanghai, China. In addition to a 3-dimensional truss analysis, each connection can be modeled as a rigid connection or a hinge connection. The test platform was idealized as a 3-dimensional truss. The axial forces and bending moments in the structural members, and displacements of the nodes in
three directions can be calculated upon loading. The nodes and members were numbered as shown in Figures 72 and 73, respectively. The dimensions of each member as constructed were used as input parameters. Double columns, double beams and beams of a smaller radius were also properly accounted for. The foundation connections were assumed to be hinge connections.

Figure 72. Node numbering of the idealized test platform in the analysis
The results of structural analysis indicate that: (1) the axial forces and bending moments in the structural members do not exceed the structural capacities of those of fir logs; and (2) the resultant displacements calculated are heavily dependent on the conditions of the connections, ranging from 0.5 mm to 76 mm, and most of the displacements occurred in the vertical direction.

However, the results of the structural analyses cannot replicate those of field measurements made on the test platform. The discrepancies can be attributed to the deficiency in the modeling of the connection joints. As the engineering behavior of the connection joints is extremely complex, it is difficult to develop a simplified numerical model to reasonably describe the engineering behavior of the connection joints for routine use in real-life engineering practice.

Results and Discussion

The design and construction of the test platform was typical of those being used in the industry. It was designed and constructed by experienced and skilled scaffolders using their empirical rules of thumb to design and their state-of-the-practice skill to construct.

A live load of 10 tonnes (approximately 6 kPa) was imposed on the platform, considerably heavier than the weight to be imposed on a working platform. The platform did not exhibit any instability or distress under the imposed load.
103. Under the imposed load, the platform settled and displaced laterally as a result of the unsymmetrical configuration of the platform. However, the lateral displacement of the platform deck was not compatible with the lateral displacements of vertical structural members measured; indicating swaying of the platform and stretching of nylon ties tying the connections on the platform deck.

104. The platform practically did not rebound upon uploading, indicating the settlement was inelastic. The inelastic settlement was probably caused by loosening of the founding soil during excavation of the platform foundation, and recompaction of the loosened soil during loading of the platform.

105. The results of the laboratory evaluation of the engineering properties of nylon ties indicate that both the strength and ultimate strain of the nylon tie are high. However, the nylon tie fails in tension in a sudden brittle mode.

106. The results of the laboratory evaluation of the engineering properties of fir logs indicate that the engineering properties of fir logs are heterogeneous. Surface hardness is not a good indicator of its strength.

107. The results of the laboratory evaluation of the connection joints indicate that the engineering behavior of the connection joints is extremely complex and heavily dependent on the workmanship of construction.

108. The numerical analysis cannot fully capture the behavior of the test platform under loading. For example, the foundation conditions and the connection conditions are not fully captured. However, the results indicate the resultant displacements of the connections are heavily dependent on the conditions of the connections assumed.

109. The foundation connection is the boundary conditions of the analysis. Therefore, these conditions have to be assumed before an analysis can be performed. In reality, the movement or settlement of the foundation connection can only be determined during the loading process. This deficit of the existing software is difficult to overcome.

110. The connection joint constructed by the tying of a nylon tie is even more difficult to model. It is neither a rigid joint nor a hinge joint. Moreover, its engineering performance is stress-dependent, as the tension in the nylon tie would affect the friction between the fir logs being tied together.

Conclusions

111. A full-scale field evaluation of the engineering performance of a fir log scaffolding platform on sloping ground was conducted at the Kadoorie Research Institute of The University of Hong Kong.

112. The design and construction of the platform was typical of those being used in slope site investigation works in Hong Kong.

113. The live load imposed on the test platform was considerably heavier than a working platform.
114. No instability or distress was observed on the test platform during the evaluation process, indicating the empirical rules of thumb adopted in the design and state-of-practice skill used in the construction of the platform by experienced and skilled scaffolders are satisfactory.

115. On the basis of the engineering performance of the test platform, it is recommended that acceptance criteria of the design and construction of temporary fir log platform for slope site investigation works should be developed on the empirical rules of thumb for the design and the state-of-practice for the construction routinely adopted by experienced and skilled scaffolders, for the best benefits of the industry, the safety of construction workers, and public safety.
Appendix I

Design Sketches of the Test Platform
PROPOSED WORKING PLATFORM
(N.T.S.)

NOTES:
1. TIMBER PLANKS NOT SHOWN FOR CLARITY.
2. A LIVE LOAD OF 10 TONNES WAS IMPOSED ON A TEST
PLATFORM OF AREA 15 SQ.M (8 kPa) AND WAS FOUND
TO BE STABLE. A MAXIMUM WORKING LOAD OF 4 kPa
ON THE PLATFORM IS THEREFORE RECOMMENDED.
CROSS-SECTION (MID-SECTION) - FLAT GROUND

CROSS-SECTION (MID-SECTION) - SLOPING GROUND

APPROX. 2000mm

APPROX. 2000mm

SOCKET IN SOFT GROUND UP TO 300mm