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Evaluation of Building Movement Using 3D Laser Scanning
3D激光扫描在建筑位移测量中的应用评估

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Abstract

High-rise buildings move during construction due to time-dependent material properties of concrete (creep and shrinkage), construction sequences, and structural shapes. To control building movements during construction a survey of movement is important as well as prediction. In this study, 3D laser scanning is introduced for a building movement survey of a 58-story (257m) building under construction located in Kuala Lumpur, Malaysia. Before the scanning of this building, movements (axial shortening and lateral displacement) due to creep, shrinkage, and irregular shapes are predicted by 3D construction staged analysis. Before the roof of the building completed, core walls and exterior structural frames were surveyed by a 3D laser scanner. As compared with prediction values, the 3D laser scanning method shows credible accuracy and efficiency for high-rise building survey.

Keywords:3D Laser Scanning, Building Movement, Construction Staged Analysis

摘要

受混凝土与时间有关的材料性质（徐变及收缩）以及施工顺序和结构构型的影响，高层建筑在建造过程中会发生位移。为了控制结构偏移，在施工阶段对位移的勘测十分重要，也可为以后的施工进行预测。本研究以位于马来西亚吉隆坡在建的58层（257米）建筑为例，利用3D激光扫描技术勘测建筑位移。在扫描之前，先根据三维施工阶段分析，对由于徐变收缩及建筑形状不规则的影响而产生的变形（轴向缩短和横向位移）进行预估。在封顶前，利用3D激光扫描仪对核心筒与外围结构框架进行勘察。相较于之前预计的数据，3D激光扫描方法对高层建筑的勘察更准确、更可信、效率更高。

关键词： 3D激光扫描、建筑位移、施工阶段分析、监测与勘察

Building Movements

Today's high-rise buildings usually exhibit some extraordinary features such as super-tall height, elevation set-backs, overhangs, or free-form exterior surfaces, all of which make construction difficult, complex, and even unsafe at some stages. In addition to the elaborately planned sequence, prediction and monitoring of the building's movement during construction and after completion are required for precise and safe construction. The building movement means vertical and horizontal displacement which results from the sum of axial and lateral deformation of vertical members at each level. The major factors affecting building movement include loads, geometry, and properties of structural members, as well as sequence of construction.

The building movement mainly affects serviceability problems. The shortened vertical structural elements inevitably transfer some forces to neighboring non-structural elements such as partitions, cladding, piping, and elevator rails, which are not designed to carry vertical load. Details for attaching these elements to the structure must be planned so that their displacement or deformation relative to the structure will not cause distress. Acceptable levels of deformation, including

建筑位移

如今的高层建筑通常都具有与众不同的特点，比如建筑超高、立面收进、悬臂结构或者不规则外观，所有这些特点都使建造过程困难复杂，甚至在某些阶段偏于不安全。此外，若要使施工精准安全，除了精心设计施工顺序外，在施工中与完工后对建筑位移的预估以及监测也是必不可少的。建筑位移是由于每层的竖向构件在轴向与侧向发生形变而导致建筑垂直与水平方向的移动。影响建筑位移的主要因素包括荷载、几何形状、构件特性以及施工顺序。

建筑位移主要影响建筑适用性。缩短后的竖向结构构件必然会将部分力传递给周边的非结构构件，例如隔墙、幕墙、管路以及电梯井道等，而这些构件的设计初衷并不承受竖向荷载。必须认真设计这些构件与结构的连接节点，避免其位移或形变对建筑物带来损害。在施工前还需考虑包括可见影响、舒适度与建筑不稳定性等在内的形变可接受程度。应考虑到邻近竖向构件不同程度的缩短变形，尤其是 高层建筑物的核心筒与周边框架柱。通常核心筒的应力小于周边框架柱，而且可能先使用滑升模板进行建造，其缩短值远小于周边柱。在建筑高层，由于竖向构件间累积的缩短变形差值，使得楼板与梁等水平构件在由于此种差异位移而产生的附加应力（

visual impact, human comfort and instability of the structure also need to be considered before construction. The effects of differential shortening between adjacent vertical members are pronounced particularly in tall buildings with a central core and perimeter columns. As the central core is generally less stressed than the perimeter columns and may be constructed in advance using climbing forms, the amount of shortening is much less than that of the perimeter columns. At higher levels of the building, cumulative differential shortenings between vertical members cause the horizontal members such as slabs and beams to tilt with resulting additional stresses (moment and shear forces) due to differential displacement. These stresses can be a significant design problem if outriggers or belt trusses are adopted in the building to resist lateral loads, since they are designed to have higher stiffness than other structural members. Another common problem due to tilted slab is the cracking or bowing of partitions when partition movement joints are not provided.

To control building movements and enhance structural safety and construction accuracy, evaluating building movement is important as well as prediction.

Monitoring Method

To monitor building movement during construction, various methods such as field measurement by strain sensors and survey using total station and GPS (see Figure 1) are introduced and used. The electronic resistance, vibration wire, and optical fiber type of gauges, which have high resolution by micro millimeter unit, are mostly used for field measurements. However, they require long wiring to connect gauges to the data logger and can measure only vertical deformation. The total station is an electronic and optical instrument used in modern surveying. The total station is an electronic theodolite integrated with an electronic distance meter to read sloped distances from the instrument to a particular point. The result of the survey is governed by the skill of the surveyor. It may induce large tolerances according to surveyor. To monitor shapes of the whole building, it requires a large amount of survey points, which can increase working time in construction fields. The Global Positioning System (GPS) is a space-based satellite navigation system that provides location and time information in all weather, anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites. To monitor movements of a whole building, a large number of GPS receivers are required and a tilt-meter, total station should be used with them. In addition to these methods, 3D laser scanning is used for the survey of architectural buildings. It is the controlled steering of laser beams followed by a distance measurement at every pointing direction. The laser scanner finds the distance of a surface by timing the round-trip time of a pulse of light. It can create a point cloud of a geometric shape on the surface of subjects. This method, often called 3D object scanning or 3D laser scanning, is used to rapidly capture shapes of objects, buildings and landscapes. The movements of a whole building can be monitored by 3D laser scanning with a short working time. This method was mostly used in low or mid-rise buildings due to the limit of scanning range. A long range laser scanner, which was developed recently and can cover over 1,000m, is applied on following project.

Field Application On KLCC Tower

A 3D laser scanner with a long range is applied on KLCC Tower, which is built right next to the Petronas Twin Towers at the city center of

弯矩和剪力）的作用下倾斜。对于在建筑结构中用承受水平向荷载的悬臂梁或腰桁架，由于这些构件比其他构件刚度大，产生的附加应力会导致较严重的设计问题。另一常见问题是当工程未提供隔墙施工缝时，倾斜的楼板会导致隔墙开裂或弯曲。

为了控制建筑位移，提高建筑安全性与施工准确度，对建筑位移的预测以及勘察十分重要。

(a)

(b)

(c)

Figure 1. (a) Field measurement by strain sensors (b) Total station (c) GPS (Source: Daewoo E&C and Leica Geosystems)
图1. (a)用应变传感器进行的现场测量结果(b)全站仪(c)全球定位系统（出自：韩国大宇工程建设公司与莱卡地勘系统）

Kuala Lumpur (see Figure 2). The height of the 58-story office building is 257m. From level 30, the plan abruptly changes from rectangle to triangle.

Building Movement Prediction

The main items of the movement prediction for the KLCC Tower are axial shortening and verticality. These two items are important for this building as its height is over 250m and the mass is eccentrically populated above certain level of the building. Structural drawings are the basis of the structural layouts, dimensional data of core walls and columns, rebar content, grades of concrete, and rebar. Members to be considered for the shortening prediction are selected by the following criteria: for symmetry of the Tower's plan and member connectivity, columns located on the lower half of the horizontal center line are considered. The concrete strength used is the mean compressive strength of the cylinder specimens at 28 days, $f_{cm} = f_{ck} + 8$ MPa. The characteristic strength of cylinder specimen fck is drawn from the characteristic strength of cube specimen f_{ck}, cube as suggested in BS EN 1992-1-1:2004. The modulus of elasticity of concrete is calculated from its strength according to ACI 318. Both the specific creep and ultimate shrinkage values are taken from PCA report (Fintel 1986). All the design loadings on vertical members are extracted by manipulating the 3-dimensional structural model of the Tower using commercial structural design software. In addition to the existing three categories of loads in the model, i.e. dead load (DL), superimposed dead load (SDL) and live load (LL), DL is further classified into vertical and horizontal members. Reduction factor for LL is chosen to be 0.5, which is sufficient as compared with the minimum 0.4 for high-rise office building such as the Tower. Creep and shrinkage components of axial shortening are influenced by the environmental conditions such as relative humidity. Relative humidity of Kuala Lumpur is set to 80%, which is taken from the BBC weather report. The loading sequence used in the analysis is based on the construction schedule planned by the site team. The core walls are set up first followed by the construction of perimeter columns and the slab outside of core walls. The slab inside the core walls are intentionally assumed to be cast at the same time as the slab outside of core walls due to lack of information and to avoid complexity. The date of application of SDL is set equivalent to the installation sequence of the curtain walls in the construction schedule and the live load is assumed to be applied on 868 days after the start of construction, which is the completion of construction.

Building Movement Prediction Methodology

Advanced analysis of axial shortening and other building movements are carried out by ASAP (Advanced Staged Analysis Program) considering the effects of real construction sequence and restraint action of neighboring structural members such as beams and slabs. The main focus is evaluating the building movement induced by the progress of construction, i.e., the increment of gravity load and time-dependent material properties. Building movement in the horizontal direction as well as in the vertical direction can be predicted at any stage of construction. Additional forces developed due to construction in horizontal members such as transfer beams, outriggers, and belt walls/trusses and the effects on other non-structural elements are evaluated. It is able to perform a construction stage analysis considering restraint action of neighboring structural members such as beams and slabs as compared with the one-column shortening analysis in C-SAP. It contains various time dependent material codes, i.e., PCA report, ACI 209, EUROCODE2, B3 model, and GL2000.

Results of Building Movement Prediction

In construction stage analysis, the movement of the Tower is analyzed

监测方法

多种方法用于在施工过程中对建筑位移进行监测，比如利用应变传感器进行现场测量，利用全站仪与全球定位系统（见图1）进行勘察。现场测量时最广泛采用的是电阻、振弦以及精确到微米的高分辨率光学纤维测量仪。然而，该仪器需要很长的电线来连接测量仪和数据记录器，并且只能测量竖向变形。全站仪是现代勘察中使用的电子光学仪器。它是结合了电子测距仪的电子经纬仪，可测量仪器至特定点之间的斜距。测量结果与测量员的技巧有关。受测量员测量技术的影响，不同测量员的观测结果会有误差。为了监测整栋建筑的形状，需要大量的测量点，这将增加在施工现场的工作时间。全球定位系统（GPS）是一种空间卫星导航系统，任何地方只要可以无障碍的联接到4个或4个以上全球定位通讯卫星，全球定位系统便可在任何情况下提供地面或地球周围的方位与时间信息。监测整栋建筑的位移要需要用到许多全球定位系统接收器以及一台全站仪。除此而外，还可以采用3D激光扫描技术勘测建筑位移。在每一指向通过操纵激光束测距。激光扫描仪通过计算光波脉冲往返仪器与建筑表面时间测算距离。它能够在目标表面生成几何状点云。这一方法叫做三维物体扫描或者3D激光扫描，通常用于快速捕获物体、建筑物以及地形形状。3D激光扫描可在短时间内监测出整栋建筑的位移情况。由于扫描范围所限，该方法最常用于中低层建筑。一种新研发的射程达1000米的远程激光扫描器将在下面的工程勘测中使用。

KLCC 塔现场应用

在KLCC 塔现场采用的是远程3D激光扫描仪。KLCC塔位于吉隆坡市中心，紧邻双子塔（见图2）。这座办公塔楼共有58层，257米。从30层起，大楼建筑平面由矩形突变为三角形。

建筑位移预测

KLCC塔的主要预测项目是轴向缩短与垂直度。由于塔高达250米，以及塔楼某层以上质量偏心，因而这两项对此建筑十分重要。结构图是结构布置、核心筒和框架柱尺寸数据、钢筋含量、混凝土等级以及配筋的基础。基于以下标准选出了预计会造成缩短的构件：考虑塔楼平面对称性及构件连通性，选取位于水平中心线下半部分的柱子。混凝土强度值采用的是圆柱试件的28天平

Figure 2. KLCC Tower (Source: Daewoo E&C)
图2. KLCC塔楼（出自：韩国大宇工程建设公司

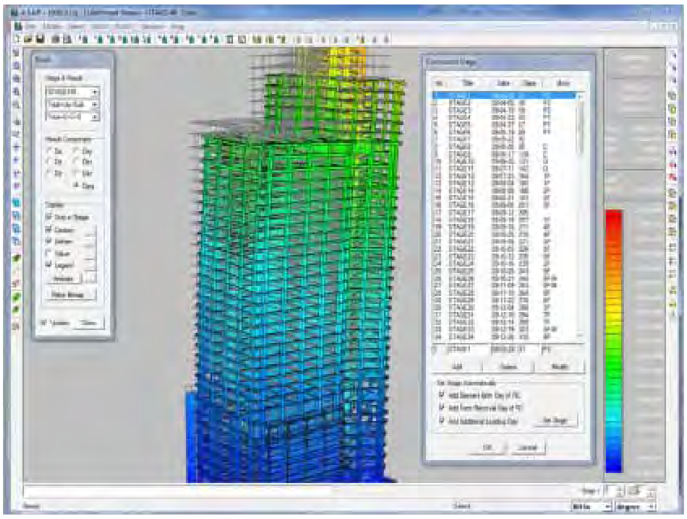

Figure 3. Construction staged analysis using ASAP (Source: Daewoo E&C)
图3. 使用ASAP法进行施工阶段分析（出自：韩国大宇工程建设公司）

in 3-dimensional space and, hence, the lateral movement of the Tower is predicted as well as the revised value of the axial shortening, which was already analyzed in one-column analysis. The average maximum value of total shortening is 115mm, which satisfies the performance target for the overall vertical tolerance and inter-story tolerance. Due to the eccentricity of the Tower's mass, shortening amounts in the triangular region are greater than those in the rectangular region but the changes in the shortening amount from one column to the next (neighboring) column is gradual so that the differential shortenings are small. This phenomenon is easily identified in the graphical presentations in Figure 3, which was not possible in one-column analysis. Distribution of lateral movement of the Tower is similar to that of axial shortening in the lateral direction – the total amount steadily increases in decreasing rate and the movements subsequent to the installation of each level slab (hereafter called as SUBTO) increases to some extent level where it decreases again. The maximum lateral movement occurs in CW2 (140mm in total and 107mm in SUBTO) and the movements of columns are somewhat lower. Up to the construction of core walls on Level 32 the Tower moves in the direction of the rectangular part and after that the Tower sways to the opposite direction (triangular part). Therefore the SUBTO component of lateral movement is bigger than total lateral movement up to Level 32.

3D Laser Scanning

Before installation of elevators at the lift core, 3D laser scanning is performed at the lift core wall (CW2), where maximum lateral movement is predicted, to evaluate the verticality of CW2 (see Figure 4). The lift core of CW2 is scanned in the vertical direction using a temporary lift. The exterior frame of the building is surveyed at the 6 scanning positions using one middle range and long range scanner. A middle range scanner, which has a scanning speed of50,000pts/sec, scanning range of300m, and tolerance of6mm, is used for surveying the lower levels of the building. A long range scanner, which has a scanning speed of 120,000pts/sec, scanning range of 1,200m, and tolerance of6mm, is used for the high level zone. The point cloud images, which have 3-dimensional coordinates of the lift core and exterior frame are presented in Figure 5 and 6.

Surveyed Results

The verticality of CW2 was evaluated based on scanning results of 9 points. The maximum lateral movement is developed at level 36 (62mm). The surveyed lateral movements increase to level 36, where the maximum value occurs, and steadily decrease again. As compared

均抗压强度，即$f_{cm}=f_{ck}+8MPa$。圆柱试件的抗压强度特征值是基于BS EN 1992-1-1:2004规定的立方体试件f_{ck}特征强度。混凝土弹性模量是按照ACI 381规范基于它的强度进行计算。徐变与极限收缩量的计算是基于PCA报告（芬特尔1986）。通过利用商业结构设计软件构件塔楼三维结构模型，提取出竖向构件所有设计载荷。除模型中现有3类荷载——恒荷载（DL）、附加恒荷载（SDL）与活荷载（LL）——之外，恒荷载还可细分为垂直向与水平向。活载折减系数设为0.5，相较于同等高度高层办公楼的活载折减系数最小值0.4足够。轴向缩短的收缩徐变构件会受到诸如相对湿度等环境条件的影响。根据BBC天气预报数据，将吉隆坡相对湿度定为80%。分析所用加载顺序是基于现场施工队制定的施工进度计划。首先建造核心筒，随后建造核心筒外的周边框架柱与楼板。由于缺少信息，并且为了避免复杂化，假定核心筒内外楼板是同时浇筑的。设定附加恒荷载加载时间等同于施工进度计划中幕墙的安装顺序。假定活荷载加载日期为施工开始后第868天，即竣工之日。

建筑位移预测方法

考虑到实际施工顺序效果与诸如梁与楼板等相邻结构构件间的约束作用，评估过程采用了高级阶段分析程序（ASAP）进行了轴向缩短与其他建筑位移的高级分析。其重点在于评估由施工过程——不断增加的重力荷载与和与时间有关的材料性质——导致的建筑位移。在施工期的任何阶段都可以预测建筑水平与垂直方向的位移。还可以预估诸如转换梁、悬臂梁、腰桁架等水平构件产生的附加力以及对其他非结构构件产生的影响。与C-SAP单柱缩短分析相比，它还能够结合梁与楼板等相邻构件的约束作用进行施工阶段分析。它囊括了多种与时间有关的材料规范，如PCA报告、ACI 209、BS EN 1992-1-1:2004、B3模型以及GL2000。

建筑位移预测结果

施工阶段分析从三维角度研究了塔楼的位移。评估结果预测了塔楼的水平方向位移，并且修正了单柱分析中给出的轴向缩短值。总缩短值平均最大为115毫米，满足竖向限值与层间限值的性能指标。由于塔楼的质量偏心，三角形区域缩短值大于矩形区值。但由于相邻柱子间缩短值呈渐变状态，其差异并不明显。通过图3的图示可以清楚的看到这一现象，但单柱分析则无法做到这一点。塔楼横向位移分布与横向的轴向缩短相类似——缩短值持续增加，但增加幅度逐渐减小。每层安装楼板后的位移会增加至某一程度后便再次减小。最大横向位移出现在CW2（整体水平位移140毫米，安装楼板后水平位移107毫米），此时柱子移动较小。在32层核心筒部分，塔楼先朝矩形区方向移动，接着又向相反方

Figure 4. 3D laser scanning for the lift core (Source: Daewoo E&C)
图4. 用3D激光扫描仪扫描电梯井道（出自：韩国大宇工程建设公司）

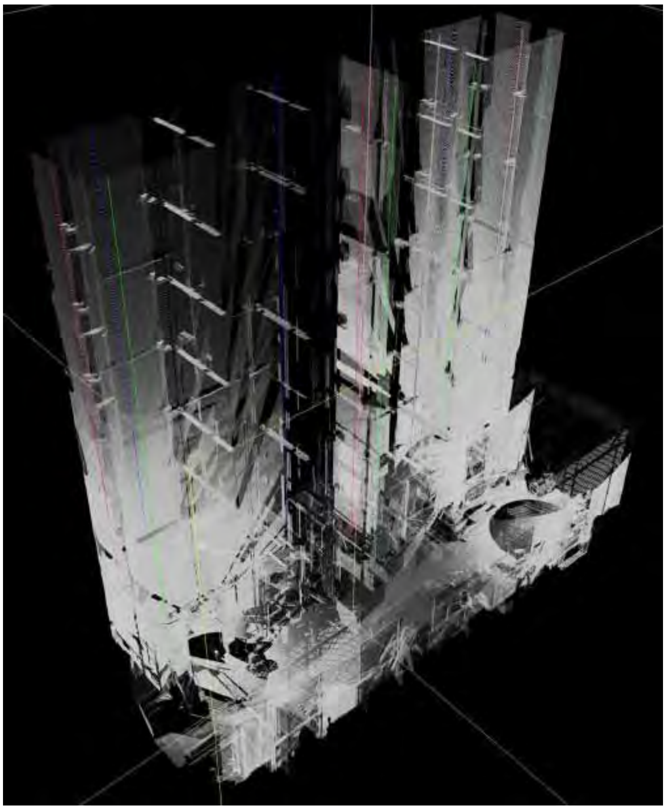

Figure 5. Point cloud image of the lift core (Source: Daewoo E&C)
图5. 电梯井道点云图（出自：韩国大宇工程建设公司）

Figure 6. Point cloud image of the exterior frame (Source: Daewoo E&C)
图6. 周边框架点云图（出自：韩国大宇工程建设公司）

with predicted movements, distribution of surveyed movements shows similar pattern (see Figure 7). The mean of differences between surveyed and predicted movements is 6mm, which is not larger than the tolerance of laser scanner. As considering tolerances of construction in addition to the tolerance of surveying instruments, the surveyed results by 3D laser scanning can be evaluated as being similar to the predicted values.

Conclusion

KLCC Tower may be the first high-rise building surveyed by 3D laser scanning. Based on these results, the verticality of core walls was evaluated.

As compared with predicted values, the 3D laser scanning method shows credible accuracy and efficiency for high-rise building surveying. It is also said that 3D laser scanning can be efficiently used in building movement control for high rise buildings.

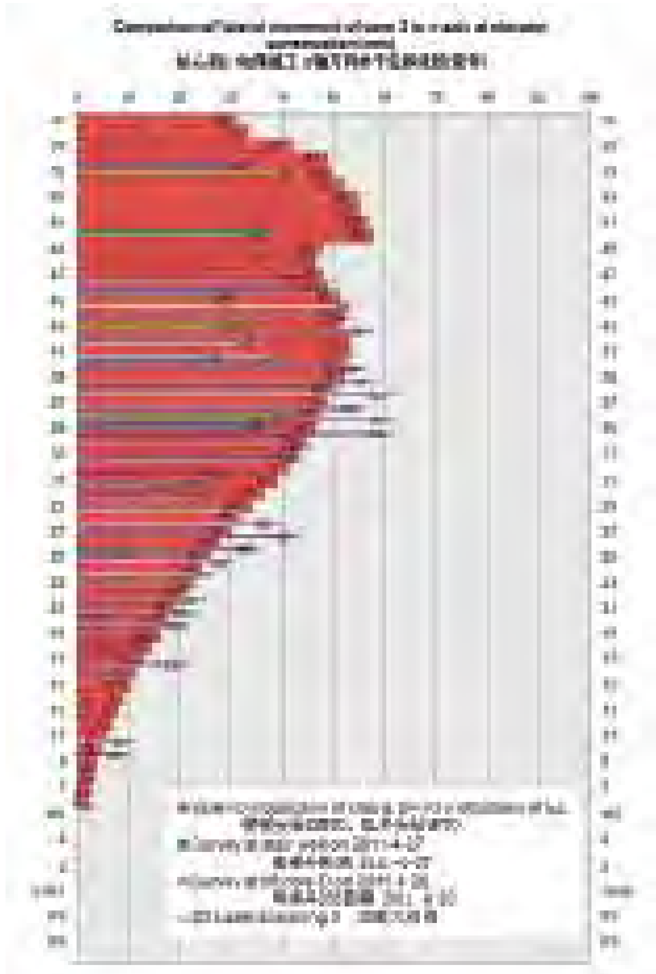

Figure 7. Comparison of lateral movement between predicted and surveyed results at lift core (Source: Daewoo E&C)
图7. 电梯井道水平位移预测值与实测值比较（出自：韩国大宇工程建设公司）

向移动（三角区）。因此直到32层，安装楼板后构件水平位移比整体水平位移幅度大。

3D激光扫描

在电梯井安装电梯前，先用3D激光扫描核心筒电梯井道（CW2，通过预估此处产生最大水平位移）以评估CW2的垂直度（见图4）。利用临时电梯在垂直方向扫描CW2电梯井道。利用中远程扫描仪在6个扫描位置扫描建筑的外围框架。用中程扫描仪勘测建筑下层。该扫描仪扫描速度为50,000点/秒，扫描距离300米，误差6毫米。用远程扫描仪勘测高层区域，该扫描仪扫描速度为120,000点/秒，扫描距离1,200米，误差6毫米。图5与图6为标有电梯井道与外围框架三维坐标的点云图。

勘察结果

对CW2的垂直度评估是基于9处扫描位置的扫描结果。最大水平位移出现在36层（62毫米）。水平位移逐渐增大直至36层，随后逐渐减小。与预测位移结果相比，勘测所得位移分布显示出类似模式（见图7）。勘测与预测的位移差值平均为6毫米，小于激光扫描仪的误差。考虑到除测量仪器之外的施工误差，3D激光扫描的勘测结果与之前预计的结果相类似。

结论

KLCC塔可能是第一个采用3D激光扫描进行勘测的高层建筑。基于调查结果，对核心筒的垂直度进行评估。

相较于预估值，3D激光扫描法在勘测高层建筑上更准确更高效。而且它还可有效的应用于高层建筑位移控制。

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