Title: **KL118 Case Study: Analysis of Different Bore Pile Testing Methods**

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KL118 Case Study: Analysis of Different Bore Pile Testing Methods | KL118 案例研究：不同基桩试验方法之采用分析

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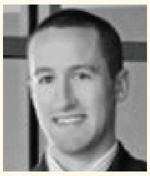

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大卫目前担任马来西亚吉隆坡Warisan Merdrka 开发案的设计和工程经理。他在西雅图和纽约市开始他的职业生涯，在那里的建筑公司工作并且拥有建筑师执照。他曾在纽约参与教育，医疗和实验室等类型专案计划。他是美国建筑师学会和LEED AP的会员。

Abstract | 摘要

In the construction of tall towers a variety of pile testing methodologies are used. Piles can be tested for many purposes including the optimization of pile design, operational verification, and quality assurance of completed piles or perhaps for design verification. The paper will provide an overview of the three types of bore pile tests conducted for the KL118 tower. Because of the various desired test results and specific site conditions, this project has used three types of bore pile testing methodologies: Statnamic, conducted on three of the 137 tower bore piles (each pile being 2.2 meters in diameter, 60 meters deep) and four of the 427 car park bore piles; Bi-directional Osterberg Cell (o-cell), conducted to verify design capacities and optimize the tower test bore piles and the car park bore piles; and Kentledge blocks, conducted once for design optimization of the car park piles.

Keywords: Bi-Directional, Kentledge, KL118, Pile Testing, Statnamic

有多种基桩检测方法可以应用于高楼基础施工。基桩试验有多种目的，包括优化桩基设计，验证施工方式及施工品质检验或与原计假设作验证。本文将提供在本专案所采用过的3种基桩试验的概述。由于所需的测试结果的多样以及工地现场的限制，本专案使用了3种类型的钻孔桩基检测方法：其中静动桩载重计共有7次试验，在承载塔楼的137支基桩（桩径2.2米，桩深60米）中进行了3次静动载重试验，另外4次用来测试地下停车场的427支基桩。为了验证设计能力，对塔楼进行优化测试，还进行了双向载重试验来验证地下停车场及商场的基桩。除此之外，我们也以呆重进行了一次静力载重试验来优化停车场基桩设计。

关键词：双向载重、呆重、KL118、基桩试验、静动载重

Introduction

In building construction, the installation of a structure's foundation is arguably one of the most critical facets, and in no building type is this more critical than a megatall tower. The testing procedure utilized to verify the proper installation and functionality of the foundation systems therefore also prevails as a critically important item, serving as the engineering confidence for which the integrity of the foundation structure is based upon.

Within the construction industry, there are four (4) principal pile testing methodologies available for testing and verification: the statnamic load test; the static maintained load test (via kentledge or reaction piles); the bi-directional Osterberg cell (O-cell) test; and the pile driving analyzer (PDA) dynamic load test. As recommended by the Engineer of Record for any given project, several factors influence the ultimate testing methodology selected, including: safety, schedule, cost, site conditions and resource availability, to name a few.

Due to the various desired test results and specific site conditions, Merdeka PNB118

引言

基础工程无疑是建筑工程中最为重要的项目之一，而对超高层建筑来说，这个说法尤其正确。正因为如此，采用适当的基桩试验方法来检测基桩能否达到原设计要求，足以承担身置其上的万丈高楼就是一个重要的课题。

营造工程业中，用来基桩承载力的检验方法主要有四种：静动桩载重试验(Statnamic Load Test)；静力载重试验（应用呆重或锚定设施），双向基桩承载试验，（Bidirectional Osterberg cell (O–cell) test）；打桩动力方析（Pile Driving analyzer (PDA) dynamic load test）.至於采用何种方法来进行基桩试验，通常是由基础结构设计单位，根据专案时程，安全性，所需费用，工地状况及可用资源等等因素来作选定。

根据以上的考量，本专案采用了三种基桩测验方法来检验基桩的承载力。本报告将就这三种方法的安全考量，试验资料收集范围及限制，所需时程及费用，作深入的分析探讨。

employed three (3) of these pile testing methodologies. An analysis of the safety aspects, data collection capabilities and/or limitations, timeframes, site conditions and relative cost implications of each will be reviewed in depth to identify how each of these concerns can be applied to megatall tower construction.

Merdeka PNB118 Project Background

Designed by Fender Katsilidis Architects and locally adopted by RSP Architects, the 630-meter-tall Merdeka PNB118 will be among the tallest towers in the world. The tower will be situated adjacent to a 140,000-square-meter, eight-story retail mall podium and together, these structures will anchor the Warisan Merdeka Development, a destination which serves to revitalize the Kuala Lumpur CBD area whilst preserving the legacy of independence of its historically significant location.

The Merdeka PNB118 structural design was led by a partnership of Leslie E. Robertson Associates and the Robert Bird Group, and was locally adopted by Arup Jurunding Sdn Bhd. The tower consists of a reinforced concrete core with eight mega-columns as well as concrete fin walls at the base. A structural steel system comprised of six belt truss zones, three outrigger zones, composite floor decks and extensive roof framing make up the main structure. The superstructure is supported by a four-meter-thick raft foundation slab and 137 cast-in-place bored piles, each 2.2 meters in diameter and extending 60 meters in length. There are 936 cast-in-place bored piles which serve as the foundation for the car park and podium structure.

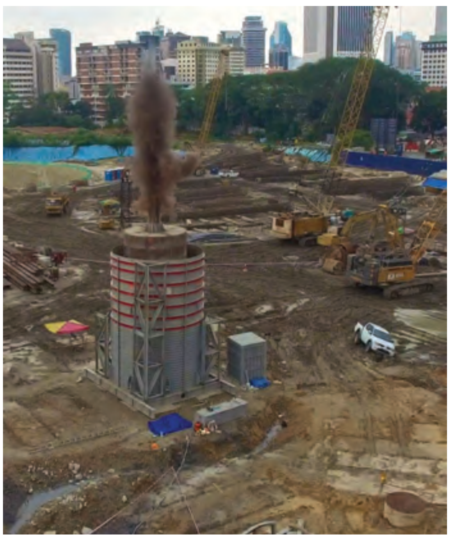

Figure 1. Statnamic load test (Source: PMV)
图1. 静载试验（来源：PMV）

Bored Pile Testing Methodologies

Merdeka PNB118 has utilized three pile testing methodologies. Statnamic load testing was conducted on three (3) of the 137 total tower bored piles and on four (4) of the 427 total bored piles at the east side of the podium. A maintained load test using kentledge blocks was conducted at one (1) bored pile and bi-directional O-cell testing was conducted at two (2) bored piles.

Statnamic Load Test

The statnamic load test is a highly specialized pile testing methodology, performed by a licensed expert, which performs a controlled burn of a solid fuel within a pressure chamber. As the pressure within the chamber increases, an upward force is exerted on a reaction mass while an equal and opposite force pushes downward on the test pile. The associated displacement of the top of the pile is measured with a laser and the data is collected with a computer, which is then used to extrapolate the pile bearing capacity. The actual test takes approximately 5 seconds, however, the staging and preparation time can extend to multiple days, depending on site conditions, pile and equipment size.

For Merdeka PNB118, an area of approximately 6m x 6m around each pile to be tested was graded and compacted for site logistics to accept the statnamic test equipment. All equipment was then erected in accordance with the approved method statement submitted by the contractor and approved by the engineer of record. Numerous safety measures were also initiated in the setup process to ensure that the explosion within the test chamber was controlled at all times. A computer was also wired to the equipment, which is used to instantaneously record all the data upon launching of the test (Figure 1).

On average, each statnamic loading test for the project took a week to set up and 2-3 days to dismantle – the test itself took seconds. Given the close proximity to neighboring residential and education buildings, several public notices were issued to the community, fire and police departments informing them of the upcoming controlled explosion and resultant loud bang. The statnamic load tests ensued in a safe, swift and efficient means to test the piles dynamically. However, availability of local or regional testing firms, site specific conditions and proximity to adjacent buildings must be evaluated closely when considering using statnamic load

Merdeka PNB118 项目简介

Merdeka PNB 118 是由来自澳大利亚的建筑师，Fender Katsilidis Architect完成主要设计然后由马来西亚当地建筑师RSP Architect 接手完成所有设计图说。这栋高630米的摩天大楼，完成后将会是世界最高建筑之一。 Merdeka PNB 118 为 Warisan Merdeka 计划的核心项目，紧邻其旁的是8层楼，总楼面积为140，000平方米的高级购物商场。这个计划不但可以创造一个新的景点，为吉隆坡中央商业区再注入繁荣动力，同时由于专案位于马来西亚宣布独立的运动场旁，这个专案也象征着承传独立国家的精神。

本专案的结构设计是由 Leslie E. Robertson Associates 及 Robert Bird Group 完成主要设计然后由马来西亚当地的 Arup Jurunding Sdn Bhd. 接手完成细部设计及图说。 Merdeka PNB 118 主要是钢筋混凝土结构；其中心为六边型的RC核心筒，搭配外围八支巨柱以及地下室的剪力墙。钢构部分则有六组belt trusses，其中三组搭配out riggers，屋顶结构，塔尖以及复合式楼版。大楼基础则是由137 支 直径2.2 米，深度达60 米的基桩加上厚达4米的基础版所构成。围绕大楼外围另外有936支基桩用来地下室停车场及其上的购物商场跟其他建筑物。

基桩试验方法

本专案一共采用过3种不同的基桩试验方法。静动桩载重计有7次试验，其中3次用来测试承载塔楼的137支基桩。另外四次则是用来测试塔楼东侧停车场及商场的427支基桩。除此之外另有一次以呆重为反力设置的静力载重试验及两次双向基桩承载试验。

静动载重试验

静动载重试验是一项需要高度专业，并且必须由领有特别执照的专业厂商执行的试验。其原理是透过控制燃烧置于压力舱的高燃速固态燃料，当燃烧使得舱内压力变大而向上推挤反力设置，于是反向且同大小的反力便作用在受测的桩头上。桩体的变位则需靠雷射仪器量测，再经过电脑运算，则可推算出基桩的承载力。整个测试过程只需约莫5秒钟，但准备及架设试验需要的设试基本上需要数天的时间，时间长短则因工地状况，受测桩及机械设备的尺寸而有所差异。

以本专案的经验而言，基本上需要一个6米乘6米大小，整平并夯实的场地来进行静动载重试验。场地准备好后，试验单位便可依照先前送审同意之施工计划及试验

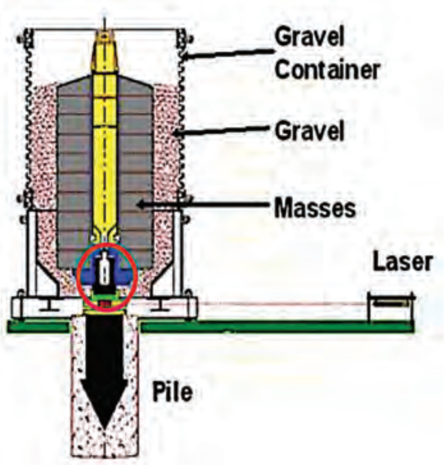

Figure 2. Statnamic load test (Source: PMV/Geonamics Pte Ltd)
图2. 静载试验（来源：PMV/Geonamics Pte Ltd）

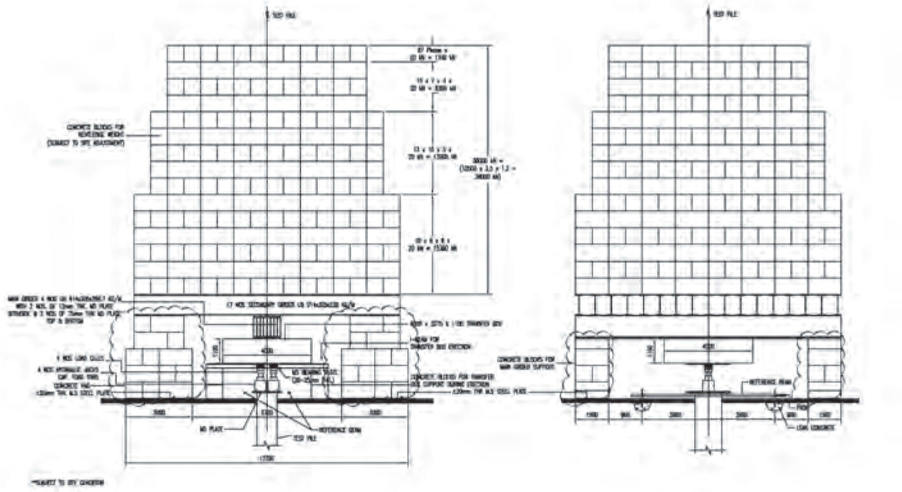

Figure 3. Kentledge diagram (Source: PMV/Aneka Jaringan Sdn Bhd)
图3. 呆重图解（来源：PMV/Aneka Jaringan Sdn Bhd）

testing as the chosen pile test methodology (Figure 2).

Kentledge Maintained Load Test

The kentledge (static) load test is a commonly used pile testing method. The capabilities of the static load test include the determination, evaluation and confirmation of the bearing capacity of a foundation pile and its apportionment into shaft friction and end bearing capacity as well as the determination of the behavior of pile settlement and the structural shortening of a pile under an applied load.

On the Merdeka PNB118 project, static load testing was performed on a working pile upon completion of the bored pile installation process, in accordance with the approved pile placement methodology by the Engineer of Record. After completing a setting out exercise and erecting a testing platform, the reaction mass (kentledge blocks) were assembled in phases from a minimum load amount to a full maintained load amount, with the specific loadings prescribed by the Engineer of Record - up to a required test load of 30,000kN. Once fully loaded, the displacement of the test pile was monitored at individual points using either a manual micrometer or electronic displacement potentiometer (Figure 3).

Figure 4. Kentledge load test (Source: PMV)
图4. 呆重负载测试（来源：PMV）

An area of approximately 20m x 20m around each pile to be tested was graded and compacted for site logistics to accept the kentledge equipment. On average, each kentlege loading test for the project took 2 to 3 weeks to coordinate and set up, 3 days to conduct the testing, and 1 to 2 weeks to dismantle and demobilize the entire kentledge assembly (Figure 4).

A drawback to the kentledge load test observed onsite is the inherent safety risks associated with it. The nature of this test method involves the stacking of extremely heavy precast concrete blocks on top of each other to spread the load across a wide area and is required to be uniformly installed to evenly distribute the load. Uneven installation of the blocks could result in the entire assembly tipping over. Additionally, site specific risk factors include the potential for crane hoisting accidents, crushing injuries, falls from height and damage to adjacent work due to falling concrete blocks. However, the kentledge load test is very cost efficient to conduct and resources are widely available within the industry.

设计开始架设试验设施。安全检查是这过程中非常重要的一个环节，正确安全的使用及管理所需的高燃速燃料尤其关键。装置完成后，结连电脑以便读取测试过程中所获得的资料（图1）。

平均而言，在本专案这样的静动试验需要一周的时间完成架设准备。试验完成后则需2至3天拆除运离试验设施。实验本身只需数秒的时间。本专案邻近数所学校，住宅及公共设施，所以在试验之前必须事先规划呈报当地公安机关及消防主管核准，并通知附近对于试验产生的巨大声响感到惊慌。静动载重试验是一个安全，快速而且确实有效率的试验方法。然而选用之前必须确认是否有合格单位能够执行这项测试，并且工地的现场情况以及周遭环境作确实评估来研判可行与否（图2）。

静力载重试验（使用呆重）

静力载重试验是一项广泛使用的基桩承载试验。它可以用来评估，判定及确认基桩的承载力以及桩端承重与桩身模擦力的比例，另外也可以判断桩体沈陷及桩身短缩与受力的关系。

本专案采用一次静力载重试验来检测部分基桩的承载力。用来提供试验所需反力的呆重为预铸混凝土块。试验载重周期则完全根据结构设计单位的规范。本次试验测试最大承载力为30,000KN. 桩受力之后，桩体沉陷量测可以用一般光学仪器或以电子仪器量测（图3）。

进行这次静力载重试验需要一个20米乘20米整平且夯实的场地来装设所需的结构设施。平均而言，类似测试如此最大载重的静力载重试验需要2到3周的准备及安装，试验本身需要3天来完成所需的载重周期，最后需要1到2周来拆除试验试备并运离现场（图4）。

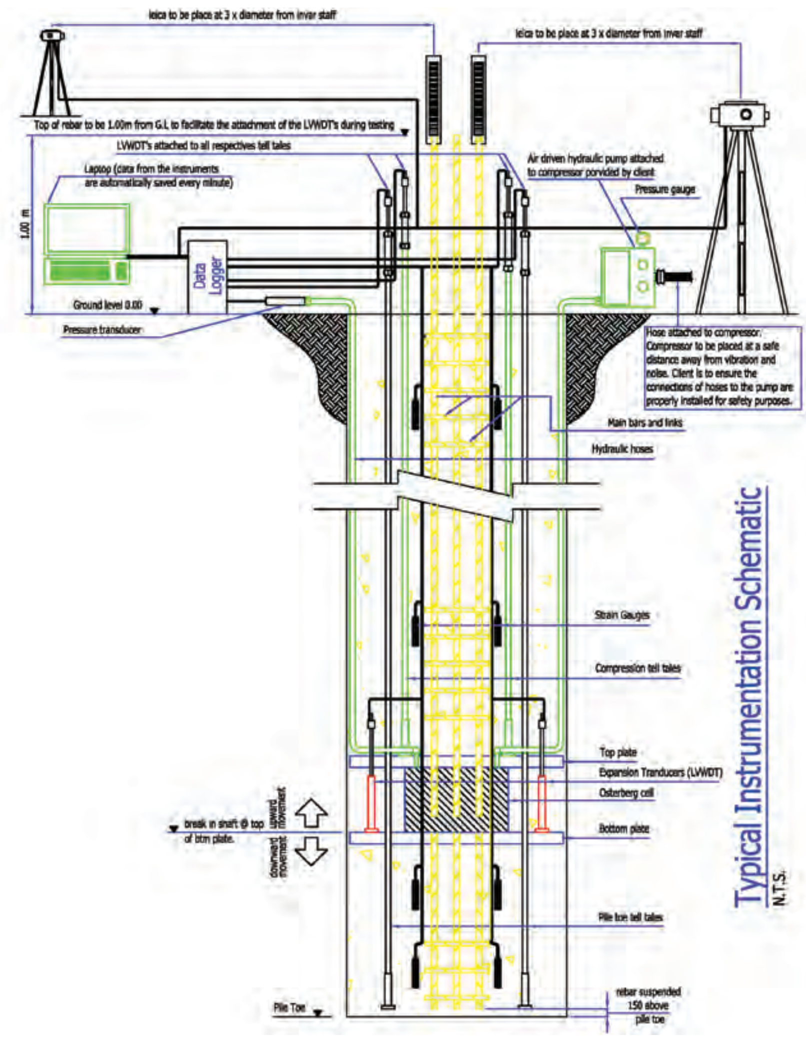

Figure 5. O-cell diagram (Source: PMV/Fugro Loadtest Sdn Bhd for Pintaras Geotechnics Sdn Bhd)
图5. 自平衡试桩图（来源：PMV/Fugro Loadtest Sdn Bhd for Pintaras Geotechnics Sdn Bhd）

Bi-Directional Osterberg cell (O-cell) Test

The execution of the bi-directional Osterberg cell (O-cell) test is typically performed on a working test pile, selected based upon site specific criteria determined by the Project Manager and design constraints determined by the Engineer of Record. Most commonly, the O-cell assembly (which consists of a predetermined number of hydraulic pistons and strain gauges) is fixed to the pile's rebar reinforcement cage via welding attachment. The O-cell testing assembly is then installed within the bored pile in accordance with the approved pile placement methodology (Figure 5).

For the Merdeka PNB118 project, the O-cell instrumentation was used to provide specific feedback as to the working characteristics of the pile such as: top of pile movement; measurement of pile compression above the o-cell assembly; measurement of pile compression in the concrete cast above the design pile cut-off elevation; measurement of the reaction pile toe displacement; and assessment of load distribution along the pile above and below the O-cell assembly.

Testing can only be initiated once the pile concrete has reached a minimum required compressive strength as prescribed by the design specifications. Upon attainment of minimum strength, the O-cell is internally pressurized via the various testing components installed within the pile. The pressurization of the O-cell creates an upward force on the pile in upper skin friction and an equal downward force in lower skin friction and end bearing. Using hydraulic fluid, pressurizing the O-cell testing equipment simultaneously loads the pile below the O-cell in downward end bearing and/or side shear which resists downward movement and loads the pile above the O-cell in upward side shear which resists upward movement (Figure 6).

During the O-cell testing the test pile is expected to break on a horizontal plane, creating an annular space within the pile. In most cases, upon completion of the O-cell test the contractor is required to grout the O-cell and annular spaces as prescribed by the Engineer of Record.

No additional working area is needed to install the O-cell assembly as it is installed within the rebar cage of the pile to be tested. However,

静力载重试验的缺点之一是安装时的安全考量。如果使用呆重作为反力，欲测试的承载力越大，则所需的呆重也越大。最常用的呆重为预铸混凝土块。要安全的完成测试，首先承载呆重的平台要设计得当并正确施作，摆放混凝土块并须依照顺序平整放置，如果平台施作不当或呆重摆设不平整，整个反力设施有可能失去平衡而倒塌。然而只要施作得当，静力载重试验实为经济而实用的试验方法。

双向基桩承载试验

双向基桩承载的原理是藉由预先设计装置在基桩内的液压系统来对于桩体施力。所以所要测试的基桩必须先经设计单位同意而后进行试验设计。设计包括所需测试的承载力，然后跟决定需要多的液压筒数量及位置。最後再决定所需的应变仪及其他量测仪器数量及量测位置。这些器材必需固定在基桩的钢筋笼，与基桩并浇置（图5）。

本专案采用双向承载试验来检验基桩在受力情况的各部分变位变型，包括桩头，在液压筒以上的桩体，桩头与液压筒之间。最后可以推算在液压筒两边桩身的受力分布情况。

试验必须在基桩混凝土达到设计强度之后才能进行。试验开始藉由液压油压如置于基桩内的液压筒，液压筒因压力而扩张向上下两部分的桩身施加大小相等，放向相反的力。桩底的压力与部分桩身短摩擦力则成为压压筒以上桩身向上反作用力（图6）。

由于液压筒的扩张，基桩在试验过程中结构上已被切成两部分。大部分的情况下，设计单位都会要求灌浆填回试验产生的间隙。

由于所需试验器材都装设在基桩的钢筋笼里，双向载重试验并不需要额外的空间来进行试验。然而根据试验的设计需要，有

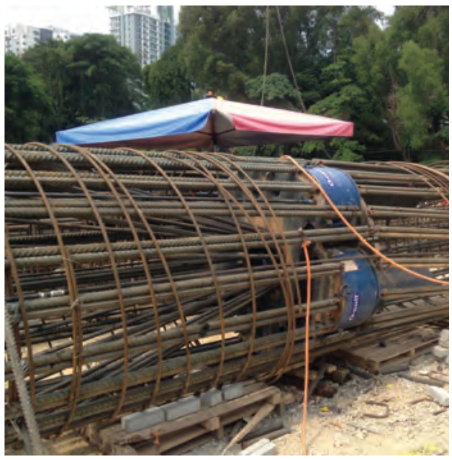

Figure 6. O-cell test (Source: PMV)
图6. 自平衡测试（来源：PMV）

Figure 7. O-cell test (Source: PMV)
图7. 自平衡测试（来源：PMV）

depending on the O-cell configuration, the procurement and delivery of the O-Cell assembly can take upwards of 2-3 months, depending on regional availability. Therefore, ample planning is needed to procure the O-cell testing assembly. Safety hazards and risks associated with O-cell testing are consistent with those typically encountered during cast-in-place bored pile construction. The greatest hazard relates to the potential for rebar cage racking during the application of the testing load and potential for malfunctioning of the O-cell test as there is no ability to repair nor service the O-cell assembly or gauges since they are cast within the pile (Figure 7).

Pile Driving Analyzer (PDA) Dynamic Load Test

Pile driving analyzer (PDA) testing involves the use of state-of-the-art equipment and computer software operated by testing specialists. The required operator expertise inherently limits the availability of licensed and qualified testers, and thus, the availability of adequate resources need always be evaluated when considering a PDA test. PDA testing is a reliable and cost effective method of assessing pile bearing capacity; however the test load limit is constrained by capacity of the weights used to conduct the testing.

The PDA test involves the use of a substantial ram mass (pile driver) that impacts the top of the pile, causing a subsequent small permanent displacement. Accelerometers and strain transducers are attached to the pile to measure force and velocity as the pile driver makes contact with the pile (Figure 8).

The testing procedure for a PDA test must account for compatibility with the testing equipment, which can be large and onerous. Specifically, this includes the selection of test piles, which are of a sufficient diameter; and normally the top of the pile to be tested must be built up to a minimum height above the ground level (typically 1+ meters). Upon confirmation of compatibility, the pile head is then fitted with gauges and transducers for measuring energy. The transducers must be attached near the top of the pile, as to

些试验所需的设计需要特别订制，而甚至需要2–3个月才能运抵现场安装。所以双向载重试验预先周延的规划以符合时程上的需要。 安全性的考量则跟一般基桩的安装相似。在吊放刚筋笼的时候除了要考虑施工安全，另外要注意避免损害安装在钢筋笼内的试验装置。任何损害都可能无法修复而导至试验失败（图7）。

打桩动力分析

这种试验需要依靠精密的仪器设备及电脑软体分析然后由专业人员来判读。所以在考虑采用这个方法试验时，必须考虑试验单位的经验，专业素养及能配合的时程。打桩动力分析是一个可靠而且费用合宜的试验方法。然而其适合范围往往受限於试验设备所能施放的重量。

打桩动力分析的原理，是让 一个足够重量的物体，掉落至欲测试的桩头上，这个外力会造成桩身的变位。藉由装置在桩身短加速度感应计及应变感传器来动取应力及速度（图8）。

采用打桩动力分析必须先考虑测试设备的适用性，所需设备可能是庞然大物。同时，待测试的桩必须有够大的桩径，并且桩头必延伸至少高于地面一米，并安装加速度感应计及应变感知器来传感能量。应变感传器必须安装在桩头部位，以确保能够读取所有能量。跟静动载重试验很类似，资料的读取跟试验同步进行，同时结束。

如果本专案采用打桩动力分析来测试桩径2.2米的塔楼基桩，设计单位要求至少要有1%的基桩设计承载力施於待测试的基桩。本案塔楼的基桩设计承载力远高于一般的

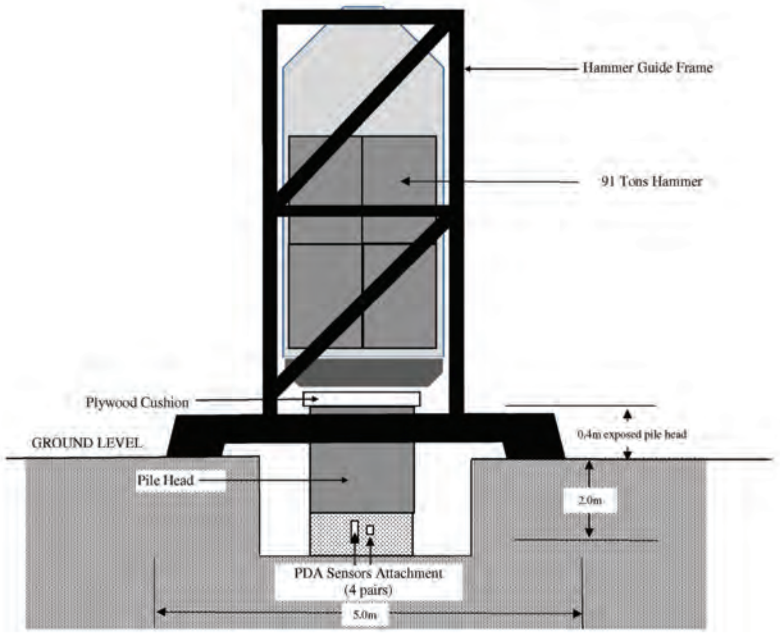

Figure 8. PDA diagram (Source: PMV/Geonamics Pte Ltd/Arup Jururunding Sdn Bhd)
图8. PDA图（来源：PMV/Geonamics Pte Ltd/Arup Jururunding Sdn Bhd）

avoid significant loss of kinetic energy during the path of travel from the pile driver impact location to the transducer location. Similar to the statnamic test, specific data can be obtained in the field almost instantaneously after completion of the PDA test.

If a PDA test was to be done on the bore piles for the tower, the Engineer of Record required at least 1% of the pile working load be achieved during the test. Due to the 2.2m diameter size of the piles for Merdeka PNB118 and the high designed working load of the piles, there was no equipment within the region of the project to conduct the testing without performing significant modifications to the testing equipment (Figure 9).

Testing Selection & Execution

In general, pile testing is utilized on a project for two primary reasons – design validation and quality control. Testing was employed early in this project for design validation, as although practical, it is not a best practice to design the piles based solely on the information obtained from the soil boring investigations at the project site. The Project Team's goal was to carefully design pile test(s) that were able to provide vital performance information to the foundation designers in order to optimize the pile design and verify the installation requirements.

Accordingly, four (4) pile tests were executed under a separate piling contract to verify the pile design for Merdeka PNB118. There were another four (4) pile tests performed for design confirmation of the piles that service the podium, and these were intentionally performed after the testing of the tower piles.

Pile testing was also utilized at the construction stage to verify the quality of installation. In most cases, pile testing for pile design is aimed to achieve pile failure in order to obtain as much information as possible. The same approach cannot be applied to pile testing that is carried out on permanent piles. As testing a permanent (working) pile is concurrent with many other activities on site, coupled with the limitations of time and space available, the testing method should be selected in concurrence with the Engineer of Record, in consideration of the following:

1. Testing loads:
The test should simulate the actual pile loading as closely as possible. Maintained loading can be achieved by the use of kentledge or via the design of reaction piles. Kentledge is the most common and economical method, however it is not suitable for piles of high working capacity, as higher testing loads require more kentledge. Normally, kentledge is selected for testing loads less than 5,000 tons. If a higher testing load is required, then an alternate testing method should be considered.

2. Reliability:
The method selected should be able to provide reliable data, as the test is carried out on a permanent pile. The test should provide very conclusive results to determine whether or not the installed pile meets the design requirements. Any ambiguity of the results would require further testing for verification, which would have potential impacts to the time and cost of the project.

3. Logistics:
The testing method selected should cause a minimum disruption to the site and its surroundings, to the greatest extent possible. The kentledge method has a large amount of logistics demands, as it requires a bigger space for setting up the system, loading the counterweights and inherent safety risks. Conversely, bi-directional and statnamic testing require very limited space to set up and perform the testing.

4. Time:
Tests on working piles should be done as early as possible, as it provides data to the Engineer to verify the method of installation. A complete kentledge method would take 3 to 5 weeks to set up, test and demobilize depending on the testing load and site access constraints. Bi-directional and statnamic methods in most cases can complete the testing from setting up to full demobilization within a week, however can require longer procurement times.

5. Cost:
Costs for pile testing need be considered on an individual project basis, as the budget and available testing resources differ greatly from project to project. On the Merdeka PNB1118 project, kentledge was found to be the most economical and widely available method to test the piles. The second most economical method observed were reaction piles, followed by O-cell. Due to the size and working loads of the tower bore piles, the more costly methods for testing were PDA and statnamic testing; the cost of performing one (1) statnamic test on Merdeka PNB118 was equivalent to the cost of installing three (3) tower piles.

Figure 9. PDA test (Source: PMV)
图9. PDA测试（来源：PMV）

基桩，在这个区域，除非特别订作或改造，没有任何试验单位有现有的设备足以承作这样规模的试验（图9）。

试验的选择与执行

一般而言，测试基桩的目的有二：一是确认设计时的假设是否正确，二是确认试工品质。本专案在设计阶段即进行了多次桩载重实验，即便许多设计基桩所需参数可以由工址地质钻探取得，藉由桩载重试验的结果，基桩设计得以优化，施工的方法及合适的施工机械也得以确认。

在塔楼基桩设计阶段，总计有4次桩载重实验来测试并提供所需的设计参数。另外有4次桩载重试验是用来提供地下室停车场及商场的基桩设计。

在施工阶段，桩载重试验也用来检验基桩的施工品质，以确认其能否达到设计的承载力。桩载重试验在这两种阶段，即便方法相同，所欲达成的目的却不同。在设计阶段的试验，基本上在设计阶段的桩载重试验是以达到破坏以取得更多资讯为目的。同样的方法则不能用在试工阶段。另外在试工阶段的试验必须考虑其他同时正在施工的项目，选择采用的试验方式，比须考量时间，场地限制，并能够达到设计单位的要求，如下所述：

1．测试承载力
桩载重试验应该尽可能模拟基桩的真实受力情况. 静力载重试验可以藉由呆重或锚定的方式来达成。最常用也最经济的反力

Analysis

Design Validation

Due to the constraints of the project site as well as the desired information that was required by the designers, the project team had to carefully consider each pile test method and compare it against the others to determine the optimal testing strategy. Ultimately, three (3) testing methods were selected for the eight (8) pile tests that were performed on the project.

During design stage testing, the bi-directional O-cell method was selected for all the tower piles. The testing program was intentionally performed in a progressive manner, to utilize the data from each test and make design adjustments accordingly prior to executing the next pile test. This strategy enabled the team to obtain the required information for design after completion of the last test pile, and ultimately the ideal design and pile construction method was determined.

For the podium structure piles, three (3) bi-directional O-cell tests and one (1) kentledge maintained load test were conducted to finalize the design. The bi-directional tests were specifically adopted for the pile locations where access was constrained.

The test piles for the podium were purposely conducted after the tower pile testing so that the previously gathered test data could be incorporated into the design. The results of the tower pile testing data suggested that an alternate balancing fluid was ideal for use in installing the piles. Due to the pile layout though, this option could not be incorporated for the tower piles. However, the option was feasible for the podium piles, and with the use of tower pile test data, a revised pile design and verification test was proposed. With confirmation received in the pile test results, the design team determined that the use of a polymer balancing fluid for the car park piles was ideal, as opposed to the bentonite material that was originally proposed. The use of this testing data to change the balancing material also enabled the car park piles to be reduced in pile by 12%, based on the performance data that was obtained. This change ultimately resulted in a proportionate cost savings and significant time reduction on the construction of piles for the Client.

Quality Control

During construction, carrying out of the required pile testing to verify the installation of the 137 piles for Merdeka PNB 118 was a challenge in and of itself. The tower piles are designed for 7,000 tons of working load, which made it extremely difficult to utilize the kentledge method. Specifically, if the kentledge testing method were adopted, at least 6,200 numbers of concrete blocks, each weighing approximately two (2) tons, would have been needed to be stacked evenly and squarely to a height of almost 9 stories to provide adequate counterweight for the testing. Therefore, this method was not considered further due to the inherent safety, schedule and logistics concerns.

For tower piles, a well-designed reaction pile system test would be able to apply the required test load, if there were site space available to install the reaction piles. However, the 137 tower piles are closely spaced within a cofferdam 78 meters in diameter, which does not allow for additional area between the tower piles to install any reaction piles.

Bi-directional testing would also be able to complete the pile testing for the tower piles. However, due to the large service load of the piles, the required load cells would have created local cross sectional congestion in the rebar cage of the piles and therefore would have potentially negatively affected the continuity of pile concrete flow during casting, eventually resulting in failure of the pile test.

Subsequently, after reviewing all available options relative to the large size of the Merdeka PNB118 piles and project site conditions, statnamic testing was selected to carry out the quality assurance testing for the piles. The statnamic testing required only one week to set up and the equipment used was able to test the piles up to 13,500 tons. The statnamic test also produced near immediate results, which provided real-time feedback as to the performance of the constructed piles.

Conclusion

Several factors must be evaluated in the development of a pile testing program. On the Merdeka PNB118 project the two most important goals of the pile testing were – to optimize the pile design and to provide design and construction assurance as to the performance and functionality of the constructed piles. Ultimately, the use of three (3) different pile testing methods were needed to achieve these goals, but the careful evaluation of the various testing methodologies and development of a strategic and specific pile testing program allowed for multiple key achievements on the project:

设施是用呆重。然而所需测试的承载力越大，所需要的呆重也就越大，安装的困难度也更大。普遍而言，只有试验承载力在5000吨以下的试验才会考虑使用呆重的静力载重试验。更多的承载力则需采用其他的试验方法。

2. 试验的可靠性

基桩试验需要可观的费用及时间，如果是用来测试实际的基桩，试验的可靠性必须很高，试验结果必须能作出肯定的结论。如果结论模拟两可，而必须施作额外的载重试验，将会对工期产生很大的影响。

3. 工地现况及动线

试验方法的选择必须尽可能避免影响其他的施工项目及工地周围的环境。使用呆重的静力载重试验需要较大的空间来组装平台及吊放呆重，安全上的考量也较高。相反的，双向载重及动静载重试验所需的空间就小很多。

4. 所需时程

原则上，施工中的载重试验应该越快完成越好，以便及早确认施工的方式是否合乎要求。视现场空间及动线规划，静力载重试验从开始架设装置到完成测试，拆解离场需要至少3–5周的时间。 双向载重及静动载重实验，如果事先设计，规划得宜，则可在一周内完成。

5. 费用

每个专案为基桩试验所编列的预算都不同。就本专案而言，静力载重试验的费用最少，其次为双向载重试验。静动载重试验最为昂贵。以本专案所需测试的载重，一次静重载重试验的费用足以支付3支塔楼的基桩。

分析

设计验证

考量基桩设计所需的资料以及工地场地的限制，专案团队必须仔细分析比较各种试验方法来决定基桩载重试验的方法。最後本专案选择了3重试验方法进行了8次桩载重试验。

在塔楼基桩设计阶段，双向载重试验用来测试以提供施工及设计所需的数据。测试以循序渐进的方式，修正假设，再测试，并在第四次试验后完成资料收集，确定了设计参数，及施工所需具备的条件。

至於地下停车场及购物商场结构的基桩，则以三次双向载重实验及一次静力载重试验来提供设计所需之数据。双向载重试验在一些动线条件很差的情况下发挥了极大的作用。

停车场及商场的基桩是在塔楼基桩设计完成之后开始试验设计的。塔楼基桩由于间

- Reduction in cost of the piling works contract

- Shortened schedule for the pile installation

- Pile design optimization

- Confirmation and verification of the constructed pile performance

- Safe and injury-free pile tests

Each mega-tower project is unique, most with a structure and foundation that is equally unique in its technical complexity and constructability to support such a project. With careful identification of the goals of a testing program, as well as a strategic evaluation of the positives and negatives of each testing method, a project team can establish a pile testing program that not only verifies the foundation pile capacity, but also contributes as another element of cutting-edge technology and industry leading engineering practices that is necessary on a mega-tower project.

距太近，设计单位设计皂土浆来保持基桩开挖的稳定。然后对于非塔楼的基桩，使用聚合物作为稳定液应更为合适。藉由另外四次以聚合物作为平衡液的载重试验，桩身设计长度得以减少12%，施工的时程及基桩费用也大幅减少。

品质管控

在施工中同时进行塔楼基桩载重试验，是一项难度相当高的挑战。由于塔楼基桩设计工作承载力将近7000吨，使用静力载重试验并不可行。理论上，假设以每块重2吨的混凝土块作为呆重，为完成这项试验则需要6200块混凝土块，平均平衡的堆叠到至少9层楼高，以提供所需的反力。理论可能而实际上不可行。

如果改用锚定桩来提供反力，理论上也是可行。但实际上由于塔楼基桩的间距过密，在这其中施作锚定桩不但困难，而且也仅能测试某部份的基桩。

另外考虑双向载重试验。同样理论上可行。然而为了达到测试的承载力，经过计算，所需要的液压筒将会占去大部分的断面积，在以特密管灌浆时，可能造成桩体不连续。因为如此试验成功的机率将受影响。

根据以上的考量，本专案决定采用静动载重试验来检测塔楼基桩施工品质。这种试验方法只需要一周时间完成，减少对工期的影响，并可测试到13,500吨的承载力。其实验结果几乎可以即时判定。

结论

在决定基桩载重试验的方法前，有许多因素必须考量。本专案采用了3种试验方式进行了多次的试验，是为了达成两项主要目标：优化基桩设计并确认基桩施工合乎设计的目标。审慎的评估及选择这些基桩载重试验方法，对本专案有以下显著的贡献：

- 减少基桩工程合约费用

- 缩短基桩工期

- 优化基桩设计

- 确认基桩施作品质及承载力

- 安全的基桩载重试验

每个超高层建筑基础工程的技术与施工的复杂程度，就如同每一个超高层建筑Ｉ样，都是独一无二的。在确认试验的目的，以及设定一个评估各种试验方式的策略后，专案团队可以建立一个多元的基桩试验计画，不但可以验证基础承载力，并可展示超高层建筑所需的先端技术与工程实务。