Title: **Tuned Liquid Dampers for the Economic Design of a Tall Building**

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Tuned Liquid Dampers for the Economic Design of a Tall Building
高层大厦的经济设计：调谐液体阻尼器

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Abstract

Rasuna Tower is an office and hotel development in Jakarta, Indonesia with 63 above-ground stories and four basements and is 280 meters tall. The lateral resistance is provided mainly by the core walls, with outrigger beams to the perimeter in the weak direction at L44. Wind tunnel testing has shown that the structure is subject to a strong cross-wind response (in its 1st mode – weak axis direction) if the building natural frequency is at the lower end of the predicted range, and that this dynamic wind response is more severe than earthquake loading. After considering various alternatives to address the significant dynamic cross wind response, the decision was made to provide additional damping in the form of a pair of tuned liquid column dampers with embedded tuned liquid sloshing dampers. Building accelerations do not require mitigation although the slightly high rotational velocities are addressed with the same dampers.

Keywords: Wind Loads, Tuned Liquid Column Damper, Dynamic Cross-Wind Response

摘要

坐落在印尼雅加达的Rasuna塔是一座以办公和酒店为一体的项目，地上63层和地下4层。塔高280米。抗侧力系统主要是由在44层的核心筒及弱方向与周边相连的外伸臂提供的。通过风洞实验得出的结论如果建筑物的固有频率是在预测范围的最小端，则建筑物会有强横向响应（在它的第一模态也就是沿弱轴方向），此大楼的风动态响应将远远大于地震荷载。通过一些方案的考量来解决此类动态横风向响应，最终决定提供一对内置晃动调谐液体柱阻尼器。虽然阻尼器会带来稍高的扭转速度，但是大楼的加速度并不会因此而变化。

关键词：风荷载、调谐液柱阻尼器、动态侧向风响应

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Introduction

Rasuna Tower is an office and hotel development in Jakarta, Indonesia with 63 above-ground stories and 4 basements. The floor plate is nominally 34m x 56m and the tower is approximately 280m tall. The lateral resistance is provided by the core walls with outrigger beams to the perimeter in the weak first mode direction at Level 44. The building is being constructed on an existing raft foundation designed and built for a 50 storey building. The floor plate design was also based on the original tower design.

Wind tunnel testing showed that the structure weak axis experiences strong cross-wind response, and that this is more severe than earthquakes. This paper discusses the dynamic wind response issues, and presents the design of the tuned liquid column damper which was adopted as a solution to reduce this response. Structure design issues as well as wind testing and damper design are discussed.

Background

The dynamic response of the building in the first 3 modes is described in Figure 1. Accelerations under service wind conditions

介绍

坐落在印尼雅加达市的Rasuna塔是一座以办公和酒店为一体的项目，地上63层和地下4层。楼板面积34米乘56米，楼高280米。横向阻力主要是由在44层支撑在核心墙周围弱方向上的支脚梁提供的。此大楼建设在筏结构基础之上设计并建造了50层，楼板的设计也是按照原始塔楼的设计而成。

风洞试验显示这个结构的弱轴将经历强横风响应，此响应甚至比地震更加严重。这篇文章讨论了动态风响应同时设计如何减少动态响应的调谐液体柱阻尼器（TLCD）。结构设计，以及抗风实验和阻尼器设计将一并在此文中被讨论。

背景

图1描述了大楼在3个模态上的动态响应在。在5到10年的风速条件下，大楼加速度处于可接受范围之内。极限状态下的基底力矩等同规范中对500年一遇地震的抵抗要求。对于极限基地力矩来说，在弱轴方向上北风对建筑物能造成非常严重的动态响应，南风对其的影响则较轻。对于第一模态（弱轴）方向而言，地基总风力矩的响应要大于地震响应。在垂直（第二模态）方向上，地震起主导作用。第一模态的行为是由于相应低的自然频率，它能降

(5 to 10 year wind speeds) were found to be within acceptable limits. It was decided that the ultimate limit state base moment is based on a return period of 500 years to be consistent with earthquake risk in the code. The ultimate base moment due to the design wind event was found to contain a significant dynamic cross-wind component about the weaker axis for wind from the north and to a lesser extent from the south wind directions. In the first mode (weak axis) direction the total wind base moment significantly exceeded the design earthquake. In the perpendicular (second mode) direction earthquake governs. The first mode behavior is due to the corresponding low natural frequencies d response. Experiences which lead to lower seismic loads while at the same time substantially increasing the dynamic loads due to cross-wind has shown that the dominance of wind loads over seismic loads has occurred previously for other slender towers in Jakarta. To design the structure to resist the full weak axis dynamic wind effects would involve additional costs in core wall thickness and reinforcement. It would also result in additional foundation reactions, which would be difficult to design for in the existing foundation.

Alternatives were discussed with the client for reducing these dynamic effects:

- Design the structure for the high base moments. This was the most expensive option.
- Modify the shape/width of the façade at the top half of the building. It has been demonstrated in a parametric wind tunnel study for a building of similar form that varying the overall dimension of the critical windward aspect by 10-15% can substantially reduce the dynamic cross-wind response of the building. This is due to a muffling of the vortex shedding frequencies over the height of the building. This alternative potentially offered the largest reduction in structure cost. The Owner preferred to maintain the straight facades so this alternative was not adopted.
- Introduce auxiliary damping to reduce the dynamic response. It can be argued that if dampers are used to control ultimate structural response under earthquake loading then there is no reason why they cannot be employed to control structural response under wind loading. Viscous dampers and tuned liquid column dampers were considered. Viscous dampers were not selected because they would need to be imported and were seen as requiring more specialist maintenance and possible future replacement.
- A tuned liquid column damper (TLCD) was the preferred option mainly because it was a closed system using simple technology. With an additional 2% auxiliary damping (making total ultimate limit state structure damping of 5%) the total building base moment could be reduced by more than 20%. The TLCD

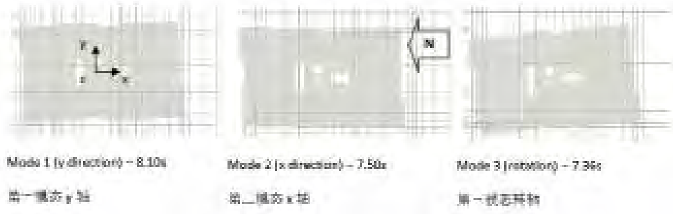

Figure 1. Mode shapes (uncracked lateral-resisting structure) (TTW)
图1. 模态（无裂痕抗侧结构）

低地震荷载，同时由于横向风响应大幅增加了动态荷载。通过经验表明风荷载相对于地震荷载占主导地位，这样的情况曾经发生在位于雅加达市的一座细长型塔楼上。为了设计能够防止弱轴动态风响应，一般采用高成本的加固核心墙的厚度和增加钢筋量。但是这样会导致很多基础的不良反应，即便如此在原有的基础结构上也会很难实现这样的设计。

与业主讨论一些减小大楼动态响应的方案：

- 针对高底部力矩进行结构设计，这是最昂贵的选择。
- 改变大楼上半部分幕墙形状或者宽度。建筑物的参数通过风洞研究表明迎风面的变化可以降低建筑物的动态横风向效应10-15%，这是由于建筑物高度产生的涡街频率消音（vortex shedding frequencies）所致。这样的设计能最大限度的减小结构的成本。但是业主坚持保留原直线幕墙设计，因此该方案未被采用。
- 引入辅助阻尼器来减小动态响应。可以说，如果阻尼器是用来控制地震荷载下的最终结构响应，那此阻尼同时也可以控制风荷载下的结构响应。有两种阻尼器提案：粘滞阻尼器阻（Viscous Dampers）和调谐液体柱形阻尼器(TLCD)。因为粘滞阻尼器阻需要进口，而且需要很专业的维护同时未来由于老化还需要更换，因此并未被采用。
- 最终采用的是调谐液体柱形阻尼器（TLCD），因为它是采用的是闭合性系统，技术相对简单。在2%辅助阻尼器作用下（总极限状态的结构阻尼器是5%），其总底部力矩能降低大约20%。TLCD的设计仅用来在极限条件下减小动态横风的响应，虽然这个设计会降低加速度，但它并且不需要控制加速度来实现。TLCD在抗地震方面可以提供一些有益效应，但是它的设计的目的并非用来减小地震响应。一般来说放置TLCD的楼层越接近楼顶起的作用越有效，但是此项目中唯一有空间放置TLCD的楼层是44层。

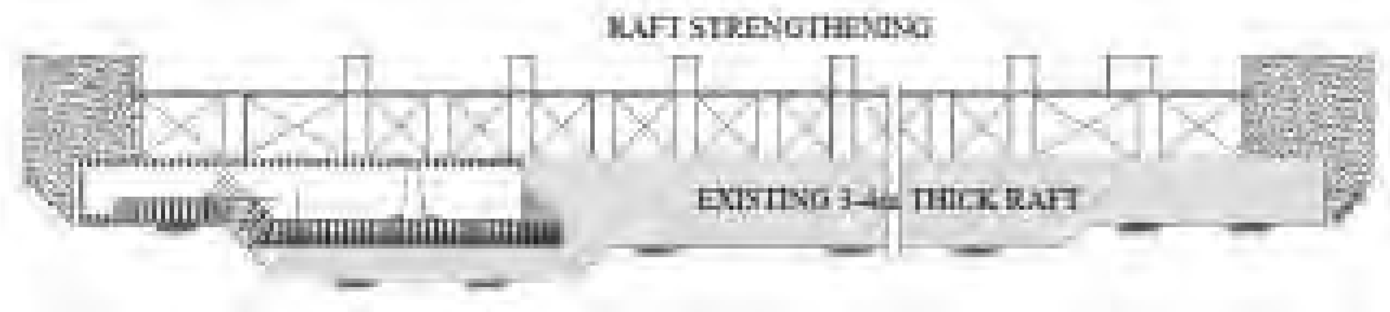

Figure 2. Raft Strengthening Section (TTW)
图2. 筏结构横截面

is designed to reduce dynamic cross-wind response under ultimate conditions only; it is not required for controlling service accelerations although it will also reduce the accelerations. The TLCD is not intended to reduce earthquake response, although it may provide some benefit in an earthquake. Space for the TLCD was only available in the plant level (Level 44) even though it would have been more efficient (meaning a smaller damper) if located nearer to the roof.

Important Design Issues

In order for the TLCD to perform effectively in the design event (ultimate wind) it is essential that the damper can be accurately tuned to the structure first mode frequency and remain in tune throughout the ultimate wind event. A number of factors create uncertainty. Important issues to be resolved in developing the structure design against dynamic wind effects in the weak axis direction included:

- Strengthening the existing raft foundation (intended for 50 stories above ground) to support 63 stories above ground, and demonstrating that the building behavior is not adversely affected by the soft foundation.
- Planning the construction sequence to allow for measurement of the structural behavior in the final stages to enable fine tuning of the damper design to match as closely as possible the natural frequency expected in the finished structure under ultimate conditions. At the same time, measuring the behavior of a full-size prototype section model of the damper.
- Ensure that the TLCD's have good performance over a relatively wide frequency range by using multiple dampers each with a different tuned frequency (nested frequencies).
- Minimize the risk of excessive cracking under ultimate conditions to ensure that the dampers remain tuned to the natural frequency of the structure.
- Providing for "large earthquake" requirements in the weak axis direction (ie to ensure certain modes of failure under an earthquake larger than the design event).
- A permanent monitoring system to be installed to enable ongoing monitoring of the building dynamic behavior and the tuning of the TLCD dampers, so that maintenance and/or fine tuning can be carried out in future if needed.

Existing Raft Strengthening

The existing tower raft was designed for a 50 storey office building and is 49m x 69m and of 3m and 4m thickness solid reinforced concrete. The top of raft (Basement 4 level) is 16m below existing ground, and 19m below tower Ground Floor. The raft is reinforced with up to 5 layers of reinforcement each way in the bottom, and 2 layers each way top. The raft soil-structure interaction for the 63 storey building was modeled using Strand7, 3-D finite element analysis software. Soil layers were modeled to dimensions of 210m x 245m x 83m depth below the raft. Stiff elements were introduced to represent the core walls, which stiffen the center region considerably. The tower raft behavior was examined including and excluding the influence of the podium raft (which did not make significant difference). Results were verified by the geotechnical engineer and by a simplified mat-on-spring foundation model.

Under the 63 storey building the existing raft (based on the soil properties) was not adequate for the design moments and shear

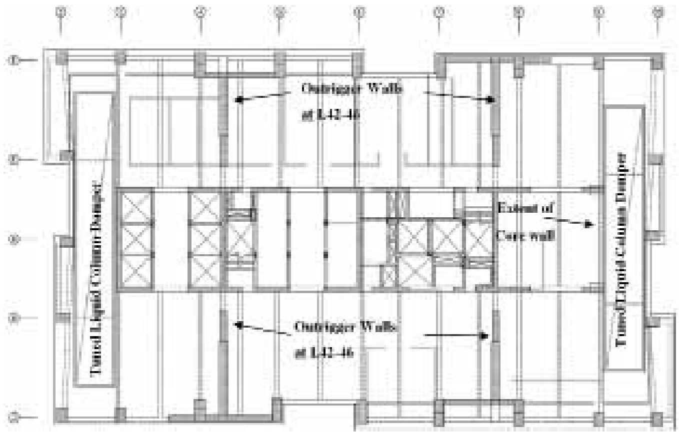

Figure 3. Floor Structure Plan at Outrigger & TLCD's
图3. 典型楼层结构平面图

设计要点

为了使TLCD在极限风荷载下也能有效地发挥作用，阻尼器可以精确地调整到第一结构频率模式，并在整个极限风事件过程中持续自动谐调。为解决动态风在弱轴方向所造成的不良结构响应，结构设计亟需解决的问题包括以下几点：

- 加固现有的筏基础结构（原计划50层楼）使其可以支持地上63层楼，确保大楼的动向不会被软基础影响。
- 有序的施工计划可以时时了解结构的动向，最后通过设计阻尼器使整体结构的自由频率符合在极限条件下的标准。与此同时测量全尺寸的原型阻尼器的节段模型动向。
- 利用多个不同调谐频率（nested frequencies）的阻尼器，保证TLCD在相对宽的频率范围内发挥良性的作用。
- 减少极限条件下过度开裂的风险，以确保减震器能继续调整并与结构的固有频率保持一致。
- 在弱轴方向上满足强震的的要求（在地震强度大于设计震级的情况下，确定失效模态）
- 一个永久的监测系统将被安装来观测建筑的动态反应和TLCD阻尼器的调谐，以便于在未来有需要的情况下，可以对其进行维护和调整。

现有筏结构强度

现有的塔筏结构是为50层办公楼其厚3到4米面积为49米乘69米的固体钢筋混凝土设计的。顶层筏（地下4层）是在现有地面以下16米，在塔地面下19米。筏结构用底部5层和顶部2层钢筋布置。利用Strand7，3D有限元分析软件模拟上方63层建筑物对底部法结构的影响。土壤层被模拟成在筏结构下面积为210米乘245米乘深为83米。刚性单元构件被用于代表核心墙，大大提高了中心筏板的刚度。塔筏结构动向的检测包括了筏结构的摆动的影响和不摆动的影响（两种情况的区别不大）。监测的结果被地质工程师检验并通过MOS基础结构模型认证。

在63层下的现有筏结构并不适用于设计的力矩，剪力与沉降。此结构在顶部加固3米深的梁格，这样可以使其和结构融合为一体。增加了6到7米深的截面与现有的底部钢筋层相结合，来支持减小建筑对风荷载的响应。如果没有阻尼器的话，只是针对力矩和剪力来设计筏结构基础是不切实际的。

结构开裂敏感性分析

在极限风荷载的情况下，需要根据建筑物的第一模态频率调整TLCD（在极限地震力荷载发生之后也是如此，尽管其破坏力并不如弱轴上风力的荷载）。阻尼器的结构频率在3-5%的公差范围内有效，这意味着实际大楼的频率在极限风荷载情况下需要在3-5%

forces, and differential settlements were excessive. The raft was strengthened by adding a grillage of 3m deep ribs on top, designed to act in composite with the existing. The combined 6-7m deep section was adequate with existing bottom reinforcement for the damped wind response of the tower. Design of the raft for moments and shear forces resulting from undamped tower motion would have been impractical.

Structure Cracking Sensitivity Analysis
Tuning of the TLCD relies on the building first mode frequency behaving predictably in the ultimate wind limit state (and after an ultimate earthquake event, which as mentioned is less severe than wind in the weak axis direction). The dampers are effective within a tolerance range of 3-5% on the structure frequency, meaning that the actual building frequency in the ultimate wind case needs to be within 3-5% of the tuned frequency or the damper will not effectively reduce dynamic response.

The effect of actual cracking on stiffness of the structure was studied under service and ultimate design load combinations. Cracking (based on Branson effective sections) was examined in the cores, link beams (door headers within the cores & outriggers), coupling beams (which couple the cores), outriggers, and perimeter frames. It was found that under approximately 25 year wind conditions significant cracking had already occurred to door header beams, coupling beams, perimeter beams and to the 8 columns supporting the outriggers and the first mode frequency reduced approximately 5% from the completely uncracked state. Under ultimate wind conditions cracking of these elements increased and new cracking occurred to the core walls below Level 8 and the outrigger elements, causing a further reduction in frequency of only 1% (ie stiffness at ultimate limit state is 1% less than the stiffness after 25 year event). This shows that the effect of cracking on building stiffness is relatively little from the 25 year to the ultimate limit state wind event. The core wall link beams showed the largest stiffness reduction with 0.63.Ig under 25 year wind and 0.5.Ig under ultimate wind. Cracking stresses to core walls occur only at the extremities.

This shows good control over building stiffness for the purpose of tuning the dampers, provided that the dampers can be tuned (and monitored, and then fine-tuned) under service wind conditions.
It is proposed that the actual dampers be tuned to a spectrum of nested frequencies based on the frequency measured at construction (analytically adjusted for building mass and stiffness effects at construction stage). Tuning frequencies from 3% above the measured frequency to 5% below represents the likely range.

Soil Parameter Sensitivity Analysis
The soil below the raft comprises deep sedimentary deposits. The short term stiffness of the soil is somewhat difficult to predict accurately. This in turn has some influence on the natural frequency of the structure.
A variation in soil stiffness of a factor of four from the "design soil properties" was studied, and resulted in a change in the first mode frequency of around 5%. This shows that the building behavior is not significantly affected by the actual soil stiffness. The compressibility of the soils would also be expected to increase the structure damping compared to what has been assumed in the design. In any case, these factors are controlled because they can be measured and monitored prior to final TLCD design.

Construction Sequencing – Outrigger and TLCD Construction
The outriggers are stiff elements which connect the core walls to the columns, and significantly increase the flexural stiffness of the tower in the weak axis direction. The design of the outriggers accommodates

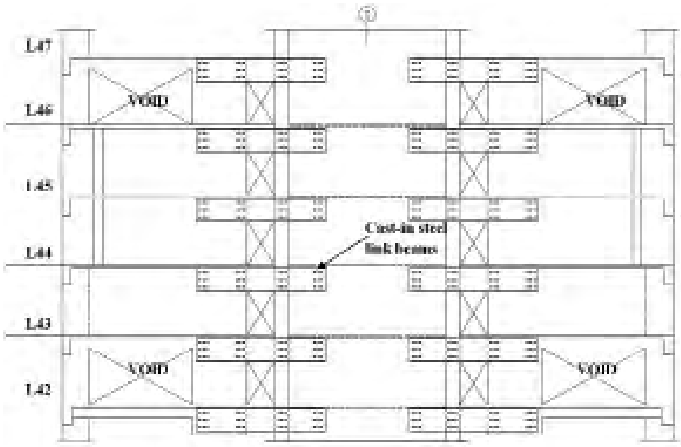

Figure 4. Core-Outrigger Lateral System Elevation at Level 42-47 (TTW)
图4. 第42-47层核心支脚横向系统

的调谐频率内，不然阻尼器将不能有效的降低建筑的动态响应。

在极限设计荷载和耐用条件下，本文研究了结构的实际断裂效应。在中心带，连梁，耦合梁，外伸臂和外围框架处的断裂程度都受到了检查。在25年的风条件下，发现在门上梁，耦合梁，周边梁和8个支撑支脚架都有显著的裂痕，另外第一模态频率在完全没有断裂的情况下减小了5%。在极限风条件下，这些构件的断裂程度增加同时新的断裂会发生在8楼以下的核心墙和支脚架构件，导致频率减小1%（比如，建筑刚度在极限荷载调价下要比这25年后的建筑刚度小1%）。这说明建筑物硬性的断裂在25年间相比极限风荷载的情况下要小一些。在25年风条件下，核心墙连接梁最大硬性减小为0.63Ig，在终极风条件下为0.5Ig。核心墙的开裂应力仅发生在墙面的末端。

在风条件下使用阻尼设备根据监测进行有效的调谐，这样能很好的控制建筑物的钢度。基于在施工时的频率测量，阻尼器需要根据频率图谱进行调谐。调谐频率在3%以上，测量频率在5%以下。

固体参数敏感性分析
在筏基础以下的土壤是很深的但较软的沉积层。在短期间内，对土壤的硬度是很难做出精确的预测的。这对结构的固有频率有一些的影响。通过对“土壤设计属性”四因素之一的土壤硬度变量的研究，土壤的硬度对第一模态频率的影响在5%左右。此数据显示，实际土壤硬度对建筑物的影响无显著的意义。相比设计上阻尼的假设，土壤的压缩性会增加结构的阻尼效应。在最终TLCD设计和监测之前，这些土壤的影响因素需要被被测量和调控。

施工顺序---伸臂桁架和TLCD的建造
支脚架是用来连接核心墙与柱的硬性构件，它能增加大楼在弱轴方向上的弯曲刚度。支脚架的设计有助于缓解柱的压缩和筏结构的变形。这些效应对结构都是不利影响。在硬性支脚架和TLCD建造之前，柱和筏结构的变形效应要给予足够的关注。

在支脚架和阻尼器放置之前，应分析大楼结构并确定它能建设的高度。在风研究中，100年的风荷载是按比例采用500年风条件下的设计荷载分析。这个方法有些保守因为风研究都是建立在幕墙已经完工的情况之下。极限标准通过分析表明核心墙的开裂不应该超过在极限条件下完整结构的开裂程度。在极限设计情况下抗拉应力在核心墙的末端是4.6Mpa，因此，极限抗拉强度的设计在这里设为4.2Mpa（比55Mpa的混凝土的核心弯曲抗拉强度4.4Mpa要略微小一点）。

分析数据显示核心墙的抗拉极限4.2Mpa在大楼的52层被达到。横向位移则小于极限的H/500。因此当结构的高度达到50层时就需要开始建造支脚架，这样既允许了阻尼器的安装也确保了封顶的时间和顶层的安全。

the envelope of long term effects in column-shortening (due to elastic, creep and shrinkage) and raft deformation. These effects are generally opposing. It is desirable to allow as much time as possible for these effects to occur before the stiff outriggers and the TLCD's are built.

To determine how high the tower could be constructed before the outriggers and damper are built the tower structure was analyzed without the outriggers. A 100 year wind load was applied by proportioning the 500 year design loads from the wind study. This approach is crude but conservative as the wind study assumes that the façade is complete (which it will not be in the construction case). The limiting criterion for the analysis was that cracking in the cores (above Ground Floor) should not exceed that expected in the completed structure under ultimate conditions. The maximum tensile stress in the extreme corner of the core in the ultimate design case is 4.6MPa. Therefore, a limiting tensile stress of 4.2MPa was adopted for this check (slightly less than the code flexural tensile strength of 4.4MPa for 55MPa concrete).

The analysis shows that the 4.2MPa core wall tension limit is achieved with the tower at Level 52. Lateral drift is within a limit of H/500. It was therefore determined that the outriggers be cast when the structure reaches Level 50, which allows the damper to be constructed and commissioned at around the time of construction of the top floors.

Large Earthquake Requirements

The earthquake code in Indonesia (as with other countries with high seismic risk) requires that the behavior of structures be controlled under earthquakes larger than the design event. The weak axis behavior of Rasuna Tower is heavily influenced by the stiff outrigger beams. The strength of these outrigger beams is governed by the steel I-section link beams connecting the deep outriggers to the core. The link beams are designed and detailed to fail in shear – acting as a "fuse" that governs total outrigger strength. Ductile behavior of the structure in an earthquake exceeding the ultimate design wind and earthquake effects is ensured as follows:

- The supporting perimeter columns are designed to resist the overstrength failure load of the link beams (Indonesia's SNI code approach is similar to the Ω_o overstrength approach of UBC-97 and in this case Ω_o = 2.8). The overstrength design was based on the shear force from all link beams at the onset of failure of the first link beam. The columns supporting the outriggers were designed to resist the resulting Ω_o earthquake forces plus floor gravity loads.
- The core walls were demonstrated by analysis to have sufficient shear strength to develop the full yield moments, and to exceed the minimum ductility required by the code.

The structure is therefore, with inelastic deformation of the core walls and other elements, capable of withstanding an earthquake or wind event of greater magnitude than the 500 year wind effects. The tuned dampers would likely not remain effective in such an event.

Tuned Liquid Damper Design

The results of wind tunnel study carried out by WINDTECH Consultants, assuming that the actual natural frequencies turn out as predicted, indicate that the TLCD will need to provide 2% auxiliary damping to the system to dampen the cross wind response to a level that is close to the peak along wind response. The energy dissipation is by means of a series of baffles and vanes as shown in Figure5b. This would increase the total system damping to 5% for the 500year event. The same

满足大震要求

印尼的地震规范要求建筑物在地震情况下控制结构的动向能力需要大于设计本身的抗风能力。Rasuma塔的弱轴动向被钢性支脚梁所影响。支脚梁的强度是由I型连接梁支配的，此梁用于连接支脚架与核心墙。连接梁的设计和细化能够确保总支脚架的强度。当地震强度超出极限风条件和地震效应的情况下，结构韧性由以下项来确保：

- 外围支撑柱是用来抵御连接梁的超强度破坏荷载（印尼的SNI设计标准与UBC-97中的最大应力值Ω_o相近，在这里Ω_o =2.8）。超强度设计基于所有连接梁中第一根达到剪力极限的连接梁。被柱支持的支脚架结构是用于抵御Ω_o地震和地板重力荷载。
- 通过分析核心墙在发生全屈服力矩的抗剪强度，需要超出规范中的最小韧度。

如果结构存在核心墙和其他构件非弹性形变，地震的承受能力或者超过500年一遇的风条件影响，类似此类事件中调谐阻尼器被认为无效。

液体调谐阻尼器设计

WINDTECH咨询公司的风洞实验结果显示，假设实际固有频率与预测一致，TLCD将需要提供2%的辅助阻尼来中和大楼的横风响应。在图5b中显示了耗能的一系列装置。同时还能在500年的事件中增加5%的总系统阻尼。TLCD也可以降低扭转响应，在55%效率中，实际计算在第三模态振动的固有频率比沿y轴摇摆的预测模态高10%（Vickery，2006）。

为了达到所需的2%辅助阻尼，相对于楼顶位置，将TLCD放置在第44层所需的总液体质量是700吨。同时建议将700吨的质量分散到3个阻尼器中。将其中两个阻尼器质量调整分别大于小于其结构固有频率，这样可以最小化在产生效应图谱时的能量，其计划是形成嵌套频率（nested frequencies）的范围。基立于阻尼器的效率，质量比和调谐性，它的范围在0.95~1.03n。这样的两个阻尼的总质量为592吨。之后用80吨的阻尼器通过2个晃动调谐槽来调整阻尼器达到实际固有频率，图 5显示了其的构造情况。阻尼器的建议配置在图2中表示出来，是通过Gao先生和Hitchcock先生发表的文章来确定的。这样的设计从自转中心到两个槽间的距离都是20米，此距离能最有效地实现抗扭转响应，其结构总质量为672吨。

据预测，在竖直柱与水平柱相同的极端情况下，涨溢大约在1.5米。因为设计的柱面积是水平截面的两倍，涨溢距离不能大于0.75米。另外限高为3.8米和阻尼器是在极端条件下设计的，为实现系统在第一模态固有频率足够低，使用双倍柱面积可以协助系统达到其固有频率。在结束设计之前，进行全尺寸模型试验，为了分析一切能影响非线性因素对阻尼的表现。另外一个永久性的遥控检测器将用于检验阻尼的工作情况。通过以下的参数可以进行调谐：a）柱中的水高度，b）水平截面的长度，c）竖直柱与其水平截面的横截面比。

调整阻尼器使其具有更高的固有频率，是可以通过减小水平截面的长度来达到的，需要较低的固有频率则是增加其水平截面的长度调整。在固有频率为0.9n的情况下，水平截面的长度表示为图 5 的11.4和14.0米增加到15.0和18.3米。经过细微调整，在水平截面的内墙里面里放置100毫米的填充物来实现稍低的固有频率，或者对竖直截面的内墙放置填充物适用于稍高的固有频率。采用的在内墙的100毫米填充物会实现1%到2%的变化，其总填充物为200毫米（单面墙是100毫米）。

以上TLD设计对峰值横向风响应效果在表 1中被列出，以下两组动态属性为：完全弹性（SLS）和裂缝（ULS）。在弱轴的底部力矩Mx和扭转效应 Mz,的变化如下表。根据Vickery的研究表明，

system is also expected to provide some reduction in the torsional response, at 55% efficiency based on the fact that the estimated natural frequency in the third mode of vibration is only 10% higher than the predicted mode for sway along the Y-axis (Vickery, 2006).

To achieve the required 2% auxiliary damping and given that the TLCD is to be placed at Level 44 rather than at the top of the tower, the total mass of liquid required is 700 metric tons. It is recommended that the mass be split into 3 separate dampers. It is planned to have two of the three masses tuned to frequencies slightly offset, either side of the natural frequency of the structure to minimize the energy in the resultant response spectrum. It is planned to target a range of nested frequencies. Based on the relationship between efficiency, mass ratio and tuning, these are most likely to be 0.95n for the damper at one end and 1.03n for the damper at the other end. These two dampers combined would account for 592 tons. A further 80 tons would be tuned to the actual natural frequency of the structure by means of two tuned sloshing tanks, with one tank embedded within each of the two TLCDs, as shown in Figure 5.

The configuration of the recommended dampers indicated in Figure 2 is determined based on research published by Gao (Gao et al, 1997) and Hitchcock (Hitchcock et al, 1997a and 1997b). The design achieves distances of 20m from the center of rotation for two of the tanks, which provides the most efficient layout to counter the torsional response. The total mass achieved is 672 tons.

It is predicted that the overshoot in the extreme case will be approximately 1.5m in the case where the area of the vertical column is the same as the horizontal column. Since the proposed column area is twice that of the horizontal section, the overshoot distance is not expected to exceed 0.75m. In addition to assisting with the issue of the limited height of 3.8m and the fact that the damper is designed for the extreme event, the doubling of the area for the column assisting in achieving natural frequencies in the system that are low enough to be tuned to the estimated natural frequency of the structure in the first mode. A full-scale mock-up test will be carried out prior to finalizing the design to analyze any non-nonlinear effects in the damper performance. In addition, permanent remote monitoring will be provided to provide regular checks on the performance of the damper. The tuning is achieved by adjusting the following parameters: a) level of water in the columns, b) the length of the horizontal section, c) ratio of the cross sectional area of the vertical columns to that of the horizontal section.

It is possible to provide a coarse adjustment to the damper configurations for higher natural frequencies by reducing the length of the horizontal section and for lower natural frequencies the horizontal section can be increased in length for frequencies down to 0.9n. Note that in the case of natural frequencies at 0.9n, the lengths of the horizontal sections indicated in Figure 5 of 11.4 and 14.0m increase to 15.0, 18.3m, respectively. After installation the fine adjustment will be in the form of applying 100mm padding inside the wall(s) of the horizontal section in the case where a slightly lower natural frequency is sought or on the walls of the vertical section in the case where a slightly higher natural frequency is sought. As a guide, the application of a 100mm padding on one wall results in a 1% change and 2% change is achieved in the case of a total of 200mm padding (100mm on each wall).

The effect of the above TLD design on the peak cross-wind response is presented in Table 1, below for two sets of dynamic properties: fully elastic (SLS) and cracked (ULS). Note that the base moments about the weak axis, Mx, as well as the torsional response, Mz, (allowing for

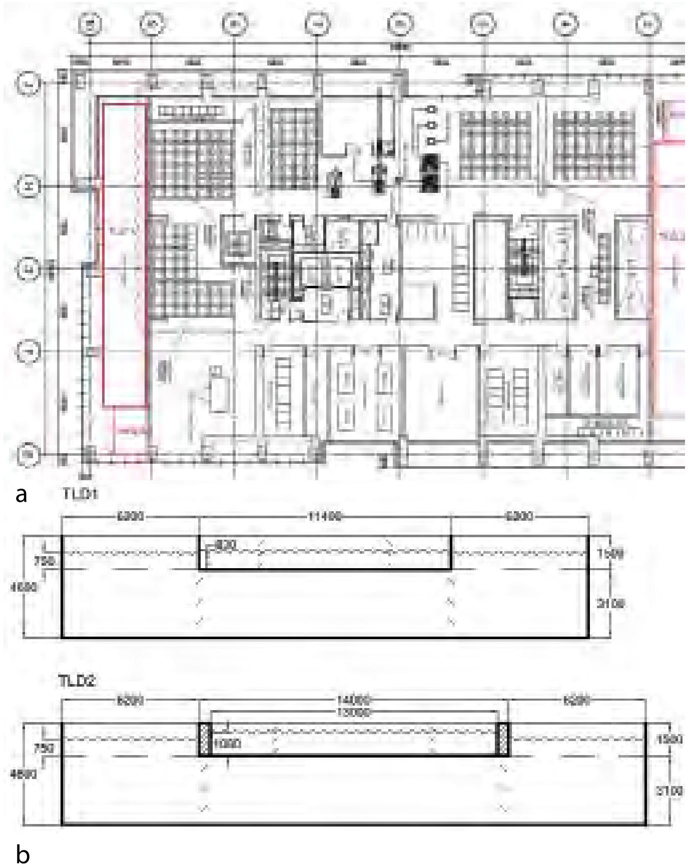

Figure 5. Tuned Liquid Damper Design (Windtech) (a) Layout in Plan (Level 44); (b) Section Views for the two Tuned Liquid Dampers on Level 44.
图5. 液体调谐阻尼器设计（Windtech）。(a).平面布置（44层）；(b).位于44层的两个液体调谐阻尼器的剖面图。

在调谐频率的基础上扭矩运动为10%，阻尼器沿弱轴方向的的效率为55%，它能有效地为扭矩系统提供1%辅助阻尼。不考虑地基提供的任何阻尼，在此类分析中采用3%的临界结构阻尼。结构一般也是有效的执行较低的固有阻尼。由于开裂的高楼阻尼数据不足，同样结构阻尼被假设有SLS和ULS两种情况。在旋转速度的情况下， 10回归年的峰值条件下结构阻尼假设为1%。

监测系统

永久的监测设备将被安装。这是连续远程操作监测数据记录系统，它包括监测阻尼器中水面的高度和测量建筑物动向的三轴加速度计。

Peak Response 响应峰值	SLS Properties SLS属性		ULS Properties ULS属性	
	No TLCD 无TLCD	With TLCD 有TLCD	No TLCD 无TLCD	With TLCD 有TLCD
M_x	4622	3749	6142	4885
M_y	2407	2407	2457	2457
M_z	304	265	331	293
Rotational Velocity	4.1	2.8	--	--

Note: 500year return moments in MNm and 10year return rotational velocity in milli-rad/s.
标注：500回归年力矩单位为MNm和10回归年转矩速度为milli-rad/s

Table 1. Peak response for the different axes for wind from the north (the most critical wind direction for cross-wind response).
表1. 北风（最重要的横风方向）对不同轴的响应峰值

lack of efficiency for torsion) will reduce as given in Table 1, below. Work by Vickery (2006) indicated that the damper for motion along the weaker axis would operate at about 55% efficiency for torsion motion based on the tuning frequency being out by 10%, effectively providing 1% auxiliary damping to the system for torsion. A structural damping assumption of 3% of critical damping has been adopted for this analysis (the expected rate of damping for a structure for 500years return wind events), ignoring any damping provided by the foundation. The structure would also perform acceptably with lower inherent damping. Due to insufficient data regarding the damping in tall buildings with cracking, the same structural damping was assumed for both the SLS and ULS cases. In the case of the rotational velocity, the structural damping assumption for the 10year return peak event is 1%.

TLCD Monitoring System

Permanent monitoring instrumentation will be installed. It is a remotely operated continuously monitored data logging system, which will include monitors for the water level in the dampers and a triaxial accelerometer for measuring building motion.

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