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DESIGN AND CONSTRUCTION OF THE JIN MAO TOWER'S MAT FOUNDATION

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ABSTRACT:

The foundation system of the 421-meter tall Jin Mao Tower in Shanghai, the People's Republic of China, consists of pile supported reinforced concrete mat. The octagonal mat is 62m x 62m in plan and 4m thick. The mat is supported by 429 deep, high capacity piles typically spaced at approximately 2.7 meter on-center to accommodate poor soil conditions. Incorporating innovative structural analyses, design techniques, and parametric studies resulted in an optimum mat size that reduced the relative deformation between the center and edge of the mat, and equalized the mat pile loads. Construction of this large Tower mat required extensive pre-construction laboratory testing to ensure the concrete mix quality. C50 concrete utilizing low-heat of hydration cement and high water reducing and retarding admixtures were specified in conjunction with a mechanical cooling system to control concrete temperature during the hydration process. A 4m x 4m x 4m reinforced concrete "test cube" specimen was designed and constructed to model the final base building mat conditions. An extensive monitoring program was specified and implemented for both the pre-construction mat "test cube" and the final Tower foundation. The monitoring included measurements of temperature gain, concrete cube testing, in-place concrete core testing, and chemical and physical (petrographic) examinations. The final Tower mat and surrounding slab areas were extensively surveyed during construction for settlement behavior. A time history of observed mat settlement as a function of Tower construction is presented. The actual measured settlements are compared with a theoretical settlement analysis. The local Shanghai construction practices for this massive concrete pour are also discussed.

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Looking from the Yangtze River toward the new Shanghai skyline, you cannot help noticing the ever changing color of the ultra-tall Jin Mao Tower with the movement of the sun as it has become the initial symbol of the new Pudong Financial District of Shanghai. With its structural topping-out, in August, 1997, the Jin Mao Tower is the tallest building in China and the third tallest building in the world. The architectural design of the building is a modern interpretation of the ancient Chinese pagoda form.

The Jin Mao project is a 280,000 m² multi-use development, including office, hotel, retail, parking and service spaces. The overall building development consists of an 88-story, 421 meter-tall Tower, and a six story low-rise retail facility. The Tower consists of 50-stories of office space topped with 38-stories of hotel with five stories of mechanical penthouse levels above the hotel. The Jin Mao site is located in the original flood plain of Yangtze River, yielding poor soil conditions and high water levels, and as a coastal site is subjected to typhoon winds, while geologically is subjected to moderate seismic forces comparable to UBC Seismic Zone 2A.

BUILDING STRUCTURAL SYSTEM:

Environmental conditions and the building's significant setbacks led to the creation of a composite hybrid structural system that is very cost effective in comparison to other ultra-tall buildings of this height. From the early inception of the design, the key structural considerations were:

- finding a structural system that is continuous throughout the building height and respects the architectural requirements and harmonizes with them.
- creating a system that utilizes the latest structural engineering and construction technological advances, while maintaining the capability of utilizing local materials and construction methods.
- managing gravity load support systems by strategically placing them in a way to maximize the efficient use of materials with minimum additional cost to also resist lateral forces.
- selecting a redundant system that has means of effective energy dissipation, and by carefully defining zones of structural "fuses" in the link beam structural system that will dissipate energy and control building behavior.
- maximizing the building's vertical extremities while optimizing structural building depth.
- preventing uplift/tension throughout the building even under extreme loading conditions.
- enhancing the inherent dynamic characteristics of the building structure to achieve acceptable dynamic behavior and response without depending on additional damping systems.

Reinforced concrete with its mass, stiffness, inherent damping, and compressive strength, when combined effectively with structural steel, with its tensile strength and lightweight composite floor framing system produces a composite system that meets all the beneficial criteria described above.

The lateral load resisting system of the Jin Mao Tower consists of an octagonal, ductile, reinforced concrete mega-core interconnected to eight exterior composite-columns through a series of structural steel outrigger trusses, spaced vertically, at optimum locations along the building height providing for the building strength and dynamic behavioral demands.

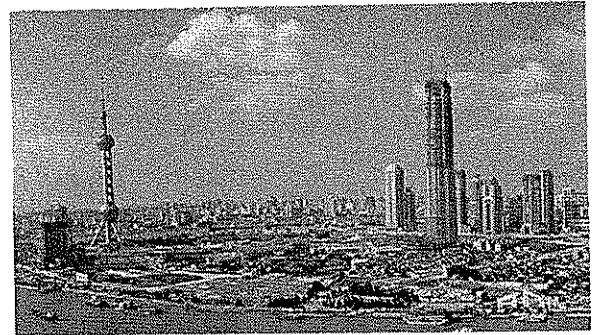


FIGURE 1: JIN MAO AND SHANGHAI SKYLINE

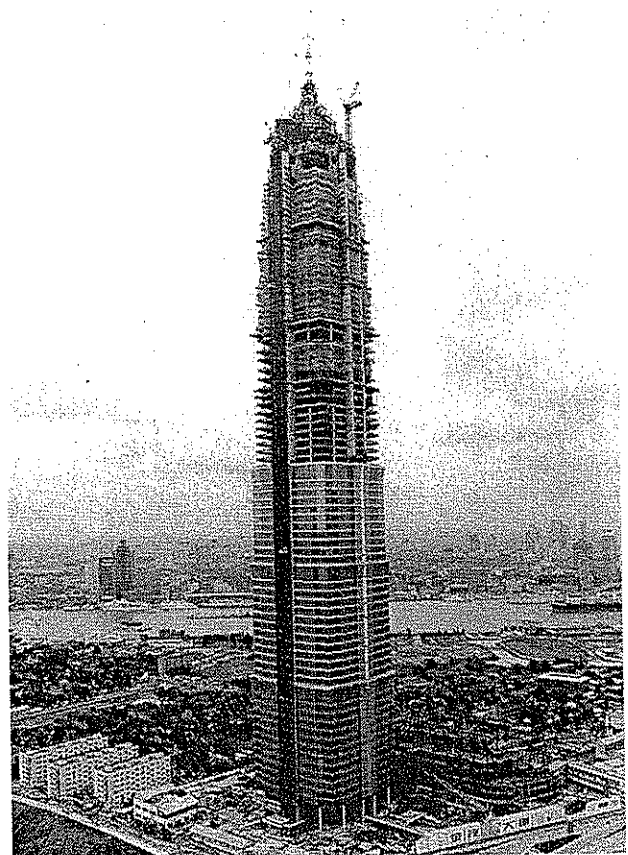


FIGURE 2: JIN MAO TOPPING-OUT

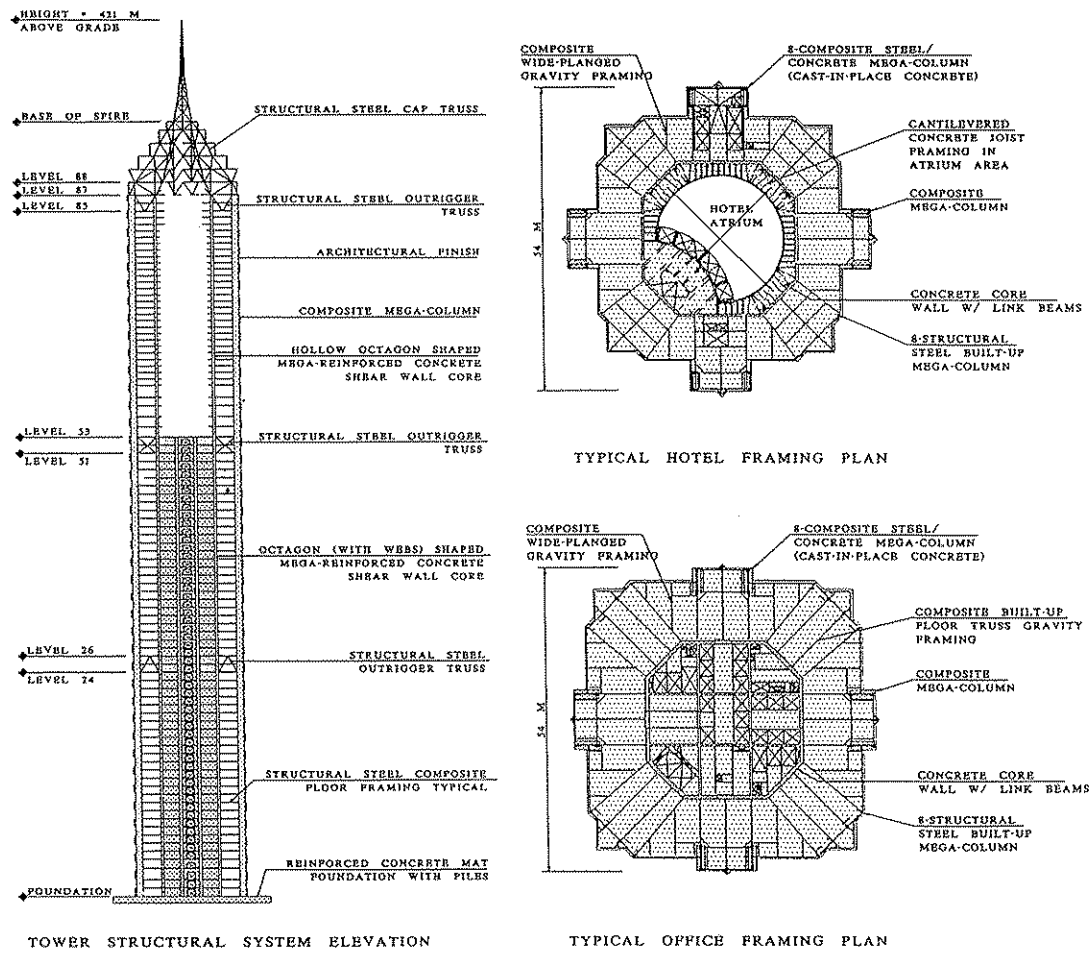


FIGURE 3: STRUCTURAL SYSTEM ELEVATION AND FRAMING PLANS

The octagonal core and the mega columns are linked by two story deep, structural steel outrigger trusses between levels 24 to 26, between levels 51 to 53, and between levels 85 and 87. The outrigger trusses at levels 85-87 are capped by a three dimensional structural steel truss system to facilitate the continuum of the structural system from level 87 to the tip of the spire. The octagonal core, nominally 27m deep, exists from the foundation to level 87 with four interconnecting web walls located within the core from the mat foundation to level 53. The central area of the core is open without web walls from level 53 to level 87, surrounding the hotel atrium, and then funnels upward into the base of the topmost spire zone. The core wall flange elements vary from 850mm thick at the foundation to 450mm thick at level 87. The core wall web elements are typically 450mm thick. The composite mega-columns vary from 1500mm x 5000mm at the foundation to 1000mm x 3500mm at level 87.

Gravity loads in the stepped back corner zones are primarily supported by eight built-up structural steel columns. The typical floor framing system consists of composite structural steel floor trusses and beams typically spaced at 4.5 meters on center, with a 75mm composite metal deck and with 80mm normal weight reinforced concrete topping.

FOUNDATION SYSTEM:

The Tower superstructure is founded on an octagonal reinforced concrete mat, measuring approximately 62m x 62m in plan, and 4m in thickness, with a C50 concrete strength. The mat is supported by 429 open ended steel pipe piles, 914mm in diameter with 20mm thick walls, spaced typically at 2.7 meters on-center under the core and mega-composite columns and 3 meters on-center under the built-up steel gravity columns. Piles, driven from the existing grade surface with 15 meter followers, are typically 65m long and driven into a deep, dense sand layer, locally described as the 9-2 stratum. The pile tip elevation is at -78.5m Mean Sea Level, which is approximately 80m below existing grade and the deepest elevation ever attempted in Shanghai.

that the piles could achieve a design load capacity well over 750 tonnes. Based on settlement criteria the depth of these piles was selected to minimize both the overall settlement and differential settlements between the building vertical support elements.

Figure 4 depicts the final Tower foundation system. The site is underlain by soft clay deposits, to a depth of 23m, and then underlain by stiffer clays and medium dense to dense sands and silts to a depth of 130 meters, the maximum explored depth. Bedrock in this area is estimated to be 300 meters below grade. Since the ground water table at the site is basically within one meter of grade, a reinforced concrete slurry wall was used as the temporary excavation retaining wall, as a permanent basement wall, and as a permanent ground water cut-off system. The wall extends approximately 0.75 kilometers around the perimeter of the site, and extends downward approximately 36 meters below grade. The slurry wall is the deepest ever attempted in Shanghai. The slurry wall system is sealed into a soil stratum having lower permeability. The effective cut-off of the ground water table allows a hydrostatic relief system to reasonably perform with a maximum design flow rate of only 30 liter/sec for the entire site. The slurry wall system is 1000 mm thick and has panel widths ranging from 4m to 6m wide. This wall is also used as a permanent foundation wall for the three levels below grade (approximately 18 meters below existing grade at the deepest areas) and is waterproofed naturally by the sodium bentonite/soil "cake" interface formed at the exterior face of the wall. After a significant pre-construction testing program for tieback system, the final temporary bracing system adopted for the slurry wall was an internal, cross-lot, diagonalized reinforced concrete strut system typically used in to Shanghai construction practice.

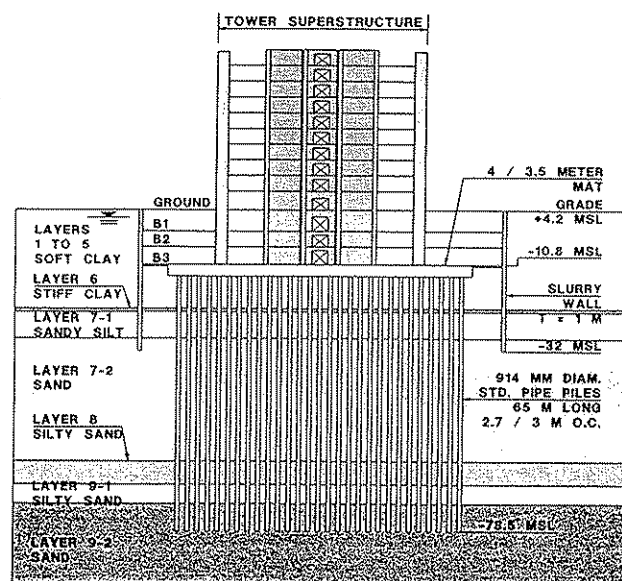


FIGURE 4: TOWER FOUNDATION SYSTEMS

MAT ANALYSIS AND DESIGN:

After preliminary sizing of the mat for both punching shear and one-way shear, a number of parametric studies were performed to determine the optimum mat thickness and pile distribution. A 4m thick octagonal mat provided the most favorable load distribution (shown in tonnes) for the optimum pile arrangement shown in Figure 5. Changing the pile spacing from 2.7m on-center below the core and composite megacolumns to 3m on-center in the more lightly loaded corner zones significantly increased the efficiency of the foundation system by limiting the number of piles.

The resultant maximum pile loads shown in Figure 5 were consistent with recommended service design loads, as verified by the pre-construction phase pile load tests and recommendations of the geotechnical consultant, Woodward-Clyde International (WCI). A three-dimensional finite element analysis incorporating the stiffening effect of the superstructure and the substructure was used for the parametric studies and the final mat design. The analysis models used 3 and 4 node, thin-plate elements to model the mat. Mat support spring elements were developed to simulate the deformation characteristics of the underlying pile/soil mass.

These elastic spring properties were provided by the geotechnical consultant based upon the three dominate soil strata and upon deformation analyses of the entire project area for the full depth of the piling-soil mass influences.

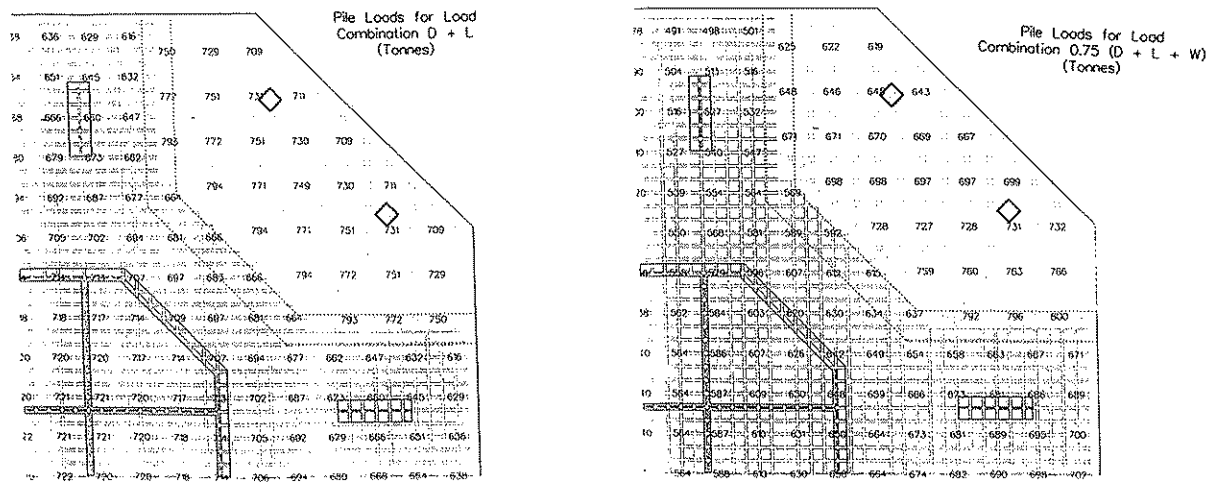


FIGURE 5: PILE LOAD DISTRIBUTION DUE TO COMBINED GRAVITY AND WIND LOADS

Based on a 11400 kN/m^3 subgrade modulus, recommended by WCI, the analyses resulted in an estimated 85mm of total settlement was anticipated under the core area with a 68mm settlement expected near the corners of the mat; this resulted in a 17-20 mm differential between the edge of the core and edge of the mat. The results are shown in Figure 6. These values are within the geotechnical settlement parameters by Woodward-Clyde International. Varying the modulus of subgrade reaction from 9500 kN/m^3 to 13700 kN/m^3 resulted in an envelope of design forces, shears and moments, for the final mat design. Structural analysis models, utilizing the concept of symmetry were performed to obtain further of refinement design moments and shears.

A soil structure finite element analysis was performed by Woodward-Clyde International based on the anticipated construction sequence and applied loadings of the structure (including excavation), as well as the stiffening effects of the Tower superstructure. This actual settlement of the Tower mat and Podium foundation system is shown as of October 1997, where building construction was 95% complete.

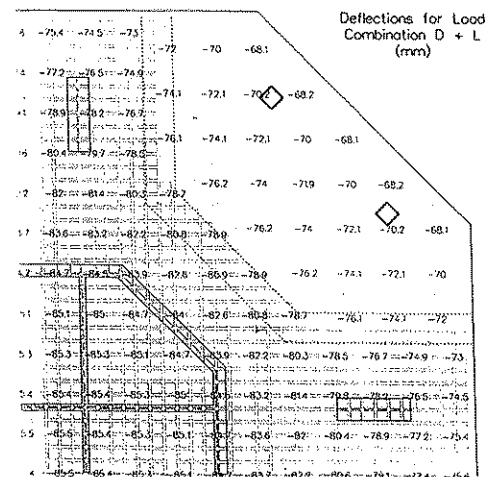


FIGURE 6: ANTICIPATED MAT DISPLACEMENT

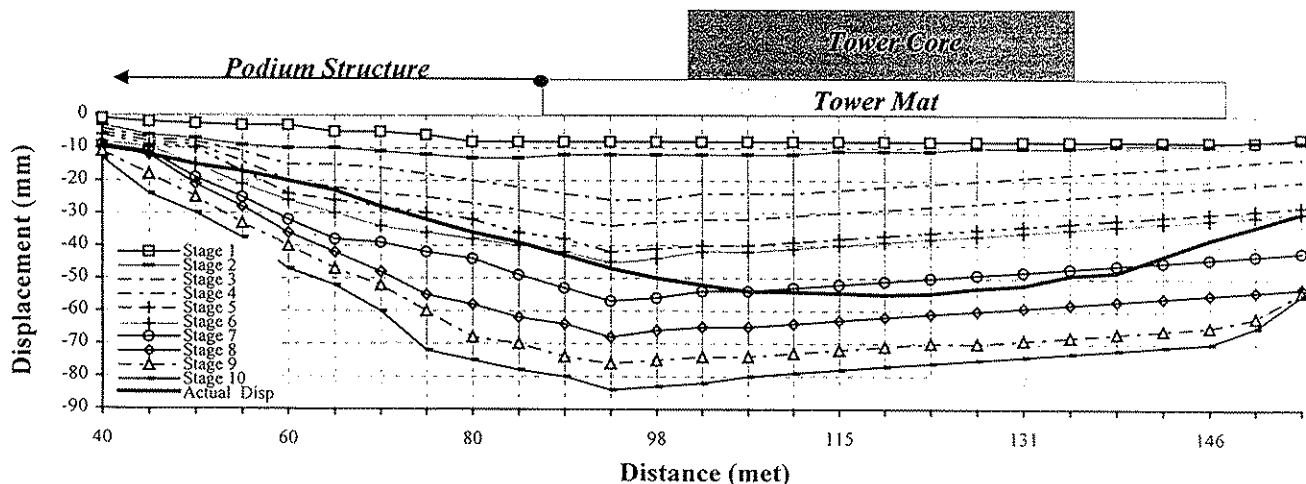


FIGURE 7: COMPARISON OF ESTIMATED VS. ACTUAL FOUNDATION

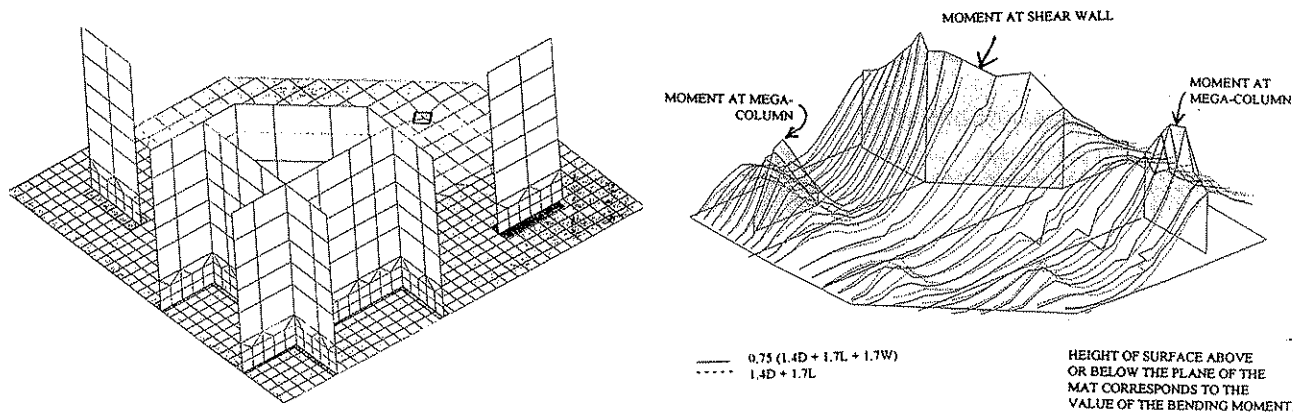


FIGURE 8: A) MAT ANALYSIS MODEL 1 B) MODEL 1 MAT DESIGN MOMENT ENVELOPE

Mat Analysis Model 1:

The mat plate elements were oriented in the plane of the mat so that bending moments in the local x and y axes were reported directly for mat design. The thickness of the plate elements correspond to the mat thickness. The core walls (modeled as plate elements), and the floor diaphragms (modeled as truss elements) were included in the model to represent their stiffening effects. The piles were modeled as spring elements at the pile locations. The thin plate elements do not provide the shear forces directly. However, the external applied loads were known and spring forces were obtained from the analysis, therefore shear forces could be computed at the critical sections for the load combination under considerations based on equilibrium. Figure 8 represents the model geometry and the design moments in the mat. To confirm the design shear forces for different load cases, the mat structural analysis Model 2 is introduced to verify the shear forces obtained by Model 1 analysis, the analysis was used to determine final bending and shear reinforcement requirements. The total reinforcing required for the mat was estimated as 1650 tonnes.

Mat Analysis Model 2:

This analysis model was the same as Model 1 except that the mat was divided into three-dimensional grid consisting of vertical plate element, normal to the mat surface. The plate elements were arranged such that they formed a grid of deep beams with intersections at pile locations. The thickness of each plate corresponded to the tributary width of each beam. Using a grid of deep beams to model the mat, this model provided means of reporting shear stresses directly. However, the torsional rigidity of the two-way behavior of the mat was lost; hence, this model was “softer” than Model 1. To compensate for the decreased stiffness, the modulus of elasticity was increased such that the pile loads in Model 2 were similar to those of Model 1.

Alternate Mat System Schemes:

In addition to studying the shape and thickness of the mat, and the spacing of the piles, the effects of additional stiffening walls were studied. Two schemes were considered where the mat was conceptualized as a “stiffened base plate” for the Tower. The first scheme added “fin walls” starting from below the ground level and protruding from the diagonal face of the core walls. The fins acted as stiffeners and helped to redistribute the load from the core to the edges of the mat. The second scheme added walls extending from the core to the composite mega-columns with walls encircling the composite mega-columns and corner steel columns. This system of walls was designed to engage the floor slab below grade, thus stiffening the mat. The advantage of using the additional walls in both schemes yielded more uniform distribution of pile loads below the mat and the thickness of the mat

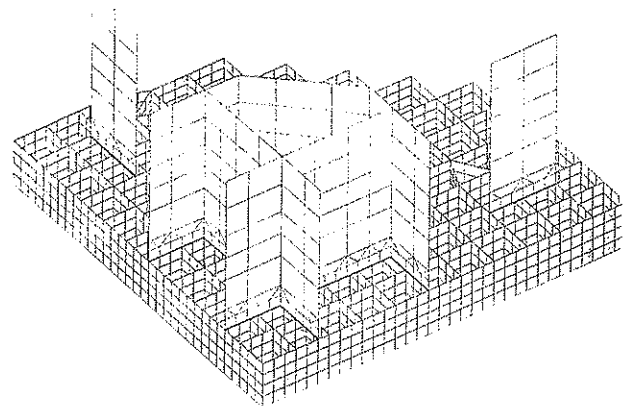


FIGURE 9: 3-D MAT ANALYSIS MODEL 2

required heavy reinforcing to resist the shear force they attracted, and more importantly were very difficult to incorporate with architectural and functional requirements of lower Tower floors. The difficulty in coordination ultimately lead to a decision not to use the alternate mat system schemes.

DESIGN SPECIFICATION FOR CONSTRUCTION:

The massiveness of the mat demanded special considerations for site preparation, construction installation and construction monitoring programs. The construction program for the Tower mat foundation, with over 14,000 m³ of concrete required that pre-construction testing be performed to verify the quality of the concrete mix, the concrete and reinforcing placement techniques, and the concrete cooling techniques used to control the temperature gain and temperature differential due to the exothermic hydration process which would occur within the mat. C50 concrete was specified for the Tower mat as well as the pre-construction "test cube" with the following criteria: a low heat of hydration cement, washed and cleaned crushed rock, clear and potable water, high-range water reducing plasticizer and retarding admixtures, acceptable fly ash, slump consistency, and controlling concrete temperature to 21° C at deposit with a maximum heat gain of 34° C. The maximum differential temperature throughout the mat was designed not to exceed 25° C by utilizing multiple layers of burlap mats as thermal insulation at the mat surface. Tables 1 and 2 indicate the foundation mat and test cube concrete mix ratios, mix properties, and compressive strengths.

TABLE 1: COMPARISON OF MAT FOUNDATION AND TEST CUBE CONCRETE MIX RATIO AND MIX PROPERTIES.

	Concrete Mix Ratio: (kg/m ³) and Mix Properties						
	Water	Cement	Medium Sand	Crushed Stone	Fine Coal Ash	EA-II Agent	Air Content (%)
Mat Foundation	190	420 (#525 type)	625	1050	70	3.36	1.7%
Test Cube	190	460 (#425 type)	473	1021	70	2.76	1.7%

TABLE 2: COMPARISON OF AVERAGE COMPRESSIVE STRENGTHS OF MAT FOUNDATION AND TEST CUBE

	Compressive Strengths (MPa)		
	Cube (Avg.)	Cylinder (Avg.)	Mat Core Samples (Min.)
Mat Foundation at 56 days	56.6	49.2	46.2
Test Cube at 28 days	50.2	NA	NA

The 4m x 4m x 4m reinforced concrete test cube was poured and monitored well in advance of the Tower mat construction. Effects of the internal heat gain within the mat due to the hydration process was a major concern, therefore, a very low heat of hydration cement (#425) was used. The mix yielded a good temperature behavior, however, the concrete strength was marginal with little increase in recorded strength beyond 28-days. See Figure 10 for the temperature variation within the "test cube". The concrete in the test cube was cast at 30° C and the highest temperature recorded within the test cube was 75° C. The temperature variation between the interior and the exterior of the mat was less than 25° C.

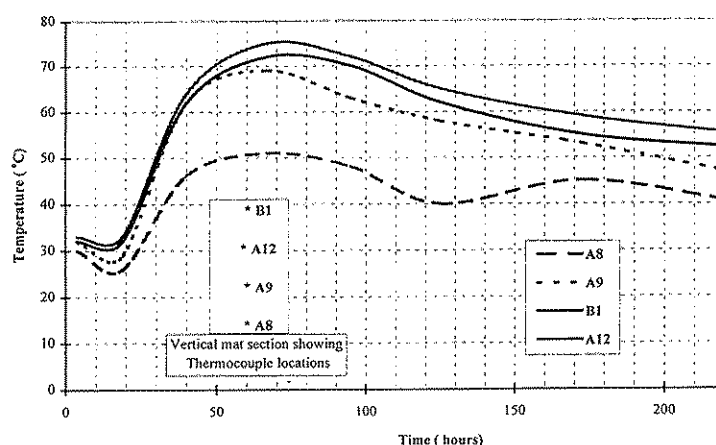


FIGURE 10: TEMPERATURE VARIATION WITHIN THE TEST CUBE.

MAT CONSTRUCTION:

The poor bearing capacity of the soil immediately below the Tower mat was not adequate to support the 34,000 tonne wet weight of the mat during construction. Therefore, the existing soil strata immediately below the mat was removed and replaced by compacted granular material capped with a lean concrete slab. In addition, pressure grouting was used to stabilize the soil within several meters below the bottom of the mat. The 14,000 m³ mat pour was completed in 47 hours. Concrete was batched off-site and brought by truck to the site on a continuous basis. Eight pumping stations were used on one side of the site with feeding placement pipes extending across the mat. Placement pipes were shortened as concrete pumping proceeded, placing the concrete continuously without cold joints.

As expected, the temperature gain in this massive concrete pour was significant even with low-heat of hydration cement and the contractor's proposed elaborate internally piped, chilled water (incoming at less than 30°C) "radiator-type" cooling system being used to control heat gain. The water temperature leaving piped cooling system of the mat reached 90° C. Insulating blankets of multiple plies of burlap was used at the top surface of the mat to control differential temperatures between the center of the mat and the top surface. A total of 100 thermocouples were used to monitor heat gain. Figure 11 illustrates the heat gain and the temperature differential within the center of the mat. Table 3 shows the initial temperature when the concrete is placed, the highest temperature, and the highest temperature rise occurred in the mat at several thermocouple locations within the mid-depth of the mat. The highest temperatures recorded are within the middle of the mat depth. Maximum recorded temperatures were higher than the "test cube" because the cement used was a different type design to yield higher compressive strengths.

TABLE 3: TEMPERATURE VARIATION IN THE MAT, CORRESPONDING TIME TO ACHIEVE THE MAXIMUM TEMPERATURE RISE

Observation Pts.	A3	B4	C3	C5	D4	D5	F3	F4	G5	H3	I5	J3	M2	Q2	R3	T3
Initial Temp.(°C)	27	29	31	31	31	30	27	30	30	37	36	29	30	30	29	34
Max. Temp.(°C)	74	90	93	94	94	97	94	90	96	95	90	70	75	72	98	71
Max. Rise (°C)	47	61	62	63	63	67	67	60	66	58	54	41	45	42	69	37
Time (h)	32	38	41	37	41	39	42	41	40	50	46	35	54	45	52	36
	North Edge				Center				South Edge				East Edge		West Edge	

Markers were placed within the mat rebar cage free areas to allow for post-coring of the completed mat and subsequent core testing to determine the physical characteristics of mat concrete. Mat core compression tests and concrete material petro-graphic examinations were performed. The in-place concrete strengths met design requirements and the micro-structure of the concrete indicated good physical properties and bond between cement paste matrix and aggregate systems.

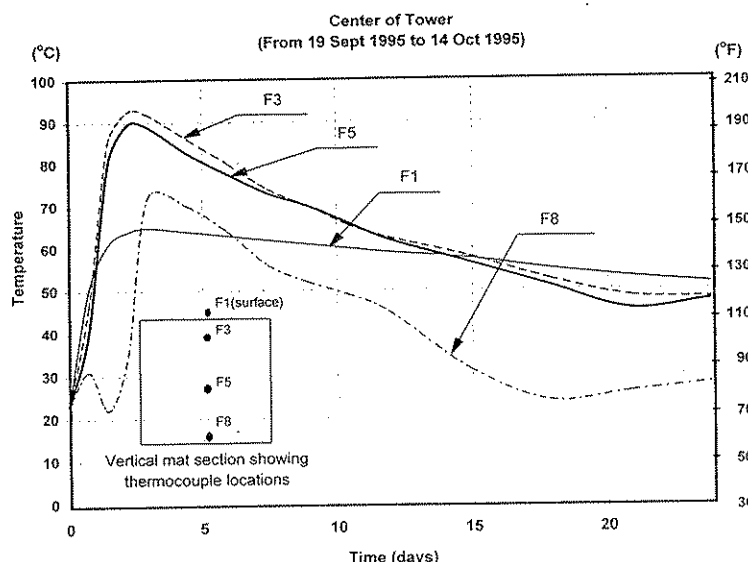


FIGURE 11: MEASURED CONCRETE TEMPERATURES IN TOWER MAT

LONG-TERM MONITORING OF THE PERMANENT MAT:

A long-term instrument survey program was specified for the Tower mat and the surrounding Podium/low-rise building areas. Special encased survey pins were located in the Tower mat and additional markers were placed on the adjacent low-rise columns to monitor long-term settlement behavior. The mat and Podium/low-rise areas were surveyed immediately after initial construction and then on a periodic basis. Figure 7 indicates total measured displacements across the site as of October 1997, while Figure 12 indicates the recorded displacements at the center and edge of the Tower mat as a function of building construction.

CONCLUSION:

The parametric analysis studies proved to be very effective in optimizing the mat thickness, reinforcement, and distribution of load from the Tower to the piles. The pre-construction mat "test cube" program was

achieve the compressive strength requirements and to verify the expected temperature rise within the mat and the effectiveness of the cooling water pipe system.

The construction organization and scheduling of the massive mat pour represents keen foresight by the contractor. Personnel and material were organized so that the 47-hour continuous pour could be accomplished without significant problems.

The temperature monitoring for both the mat "test cube" and the final tower mat provided extremely useful information regarding maximum heat gain, heat radiation as a function of time, and relative heat gain between the center, and top and bottom surfaces of the mat. Long-term displacement monitoring confirmed the expected "dishing" behavior of the Tower mat as well as the expected overall long-term displacements. The displacement influence of the Tower on neighboring Podium/low-rise areas was also confirmed by in-situ surveying.

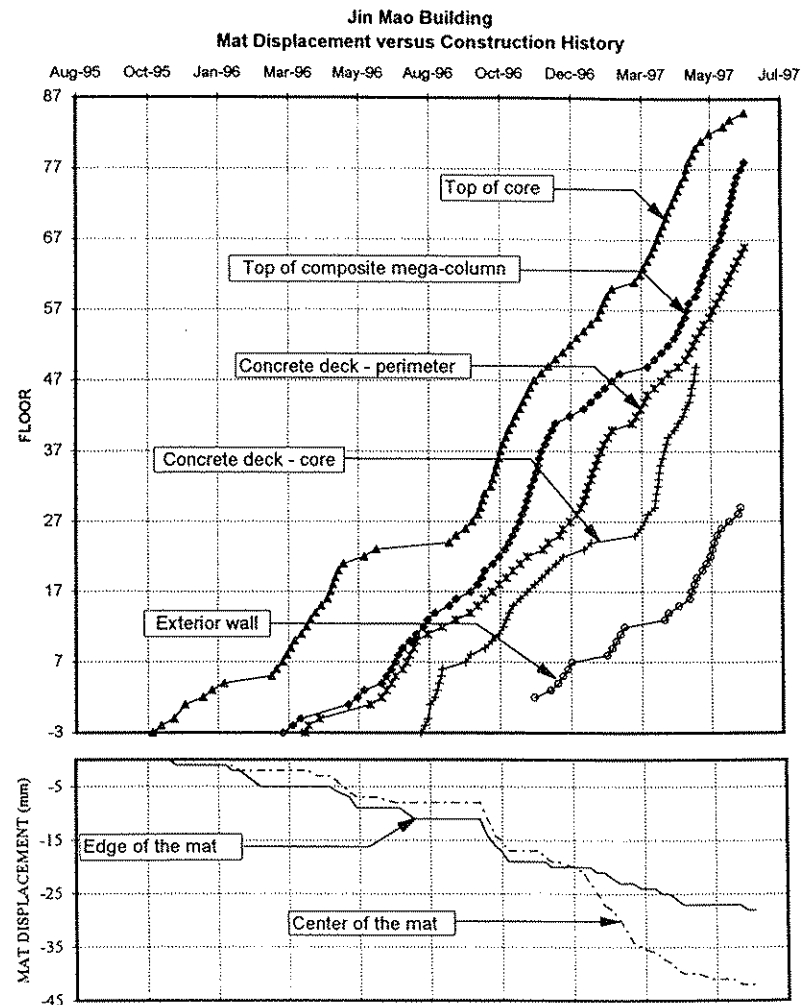


FIGURE 12: MEASURE DISPLACEMENT OF TOWER MAT

ACKNOWLEDGMENTS:

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- ◇ Associate Architect / Engineer (Design): Shanghai Institute of Architectural Design and Research
- ◇ Associate Architect / Engineer (Construction): East China Architectural Design and Research Institute
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- ◇ Geotechnical Consultant: Woodward-Clyde International, Shanghai Institute of Geotechnical Investigation and Surveying