Title: **The Role of Peer Review in the Foundation Design of the World's Tallest Buildings**

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Clyde N. Baker

Mr. Baker received his BS and MS degrees in Civil Engineering from Massachusetts Institute of Technology and joined the staff of STS Consultants, Ltd. (formerly Soil Testing Services) in the fall of 1954. Over the past 50 years he has served as the geotechnical engineer on the major portion of high rise construction built in Chicago during that time frame. He has also served as geotechnical engineer or consultant on seven of the sixteen tallest buildings in the world including the three tallest in Chicago (Sears, Hancock, and Amoco) and the current three tallest buildings in the world, the Petronas Towers in Kuala Lumpur, Malaysia and 101 Financial Center inTaipei, Taiwan.

He is the recipient of the Deep Foundation's Institute Distinguished Service Award, the ADSC Outstanding Service Award, ASCE's Ralph B. Peck, Thomas A. Middlebrooks and Martin S. Kapp Awards and of three Meritorious Publication Awards from SEAOI including the "History of Chicago Building Foundations 1948 to 1998" and is the author of "The Drilled Shaft Inspectors' Manual". Mr. Baker is an Honorary Member of ASCE, a past President of SEAOI and the Chicago Chapter of ISPE, a past Chairman of the Geotechnical Engineering Division of ASCE, a past Editor of the Geotechnical Engineering Journal and a past Chairman of ACI Committee 336 on Footings, Mats and Drilled Piers. He is a member of the National Academy of Engineering and in 2006 received The Moles 2006 Non-Member Award for "Outstanding Achievement in Construction".

Mr. Baker is a past Chairman of STS Consultants, Ltd., a 550 person consulting engineering firm, headquartered in Vernon Hills, Illinois and currently serves as Senior Principal Engineer and Senior Vice President.

Tony A. Kiefer

Mr. Kiefer received his Bachelor's and Master's Degrees in Structural and Geotechnical Engineering at the University of Illinois-Chicago. He has over 23 years experience in subsurface exploration, seismic analysis and deep foundations. As an Associate Engineer at STS Consultants, Ltd in Vernon Hills, Illinois, Mr. Kiefer has been the geotechnical engineer of record for more than 50 high-rise building projects constructed on deep foundations in Chicago. These projects have included the proposed 112-story, 7 South Dearborn project, the 89-story Waterview Tower, the 67-story One Museum Park, the 70-story Park Hyatt Tower, the McCormick Place Hotel and West Hall Expansion, and the expansive Central Station Development of more than 20 high-rises.

Mr. Kiefer has been a consultant for deep foundation projects in Florida, Missouri, New York, Las Vegas, Poland, Russia, China, Korea the Caribbean and the Middle East. Mr. Kiefer has acted as peer reviewer or principal engineer for some of the tallest buildings in the world including the Lotte Tower in Seoul, South Korea, the Doha Convention Center and Tower in Qatar, the Central Market project in Abu Dhabi, and the proposed world's tallest building, the Palm Tower in Dubai, U.A.E. He was also one of the principal investigators in a joint ADSC/FHWA research program on Free Fall Concrete in Drilled Shafts.

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Abstract

This paper presents the authors' views based on experiences on the role of peer review in the cost effective foundation design of very tall buildings. Different types of peer review and possible scopes are described along with relevant recommendations. The reasons for hiring a peer reviewer and the advantage of having the peer reviewer involved from the beginning at the start of the design team meetings are outlined. The problems and questionable value of after-the-fact peer reviews are discussed. The role of value engineering early in the review process, as well as the value of local experience in modifying the views of the peer reviewer, is also presented. The views presented are illustrated by brief case history descriptions including: Petronas Towers, TNC Tower, Taipei 101, Burj Dubai, Doha Convention Center and Tower, and Chicago high-rises.

The paper concludes with an endorsement of the value of the involvement at the earliest stage in the design process of a foundation peer reviewer with international experience in the types of foundations being considered and the required geotechnical criteria needed for a super-tall structure. This international experience combined with the input and knowledge of the local geotechnical practitioner can best develop the most economical and sound foundations.

Keywords: Peer review; cost effective foundations

Introduction

Peer review can be defined in general terms as the process of subjecting an engineer's work, research or ideas to the scrutiny of others who are experts in the same field. It is commonly used by editors to select and screen manuscripts or papers submitted for publication in technical or scientific journals. In this situation, the peer reviewer is not involved during the development of the paper and there is no direct communication between the peer reviewer and the person whose work is being reviewed. The peer review process aims to make authors meet the standards of their discipline and of science in general. However, the peer review process can be used in other areas as well. This paper discusses the authors' experience in how the peer review process has been applied to the cost effective foundation design of the world's tallest buildings. In this case there is the potential for involving the peer reviewer early in the foundation design process.

The goal of any foundation designer is typically to develop a design that is both cost effective and safe and meets any required settlement and performance criteria. If the peer reviewer's scope includes working with the design geotechnical engineering firm, in a collaborative as well as review role, maximum project benefits can result.

Internal Peer Review

Some engineering firms on major projects have an internal peer reviewer in addition to their normal checking procedures. The internal peer reviewer has no direct line responsibility but serves as an in-house consultant because of his recognized experience and expertise.

External Project Peer Reviews

If there is going to be a peer reviewer outside of the design geotechnical engineering firm, it is important that the selected peer reviewer be recognized as competent, with an international reputation and recognized expertise. This is particularly important if the peer reviewer is retained by the project developer as it makes it more likely that the peer reviewer's views will be given careful consideration by the geotechnical design engineer.

It is also important that the peer reviewer be a team player with a respectful and professional attitude toward the engineer's work being peer reviewed. This makes far less likely that there will be prolonged engineering disagreements, confrontations and project delays. At the same time, the peer reviewer must have integrity to speak his mind clearly on controversial engineering issues where there is a disagreement even when his client prefers the view of the engineer being reviewed. This is particularly important in the geotechnical field where judgment plays a major role in arriving at the appropriate engineering solution.

Why Retain a Peer Reviewer

It is anticipated that retaining an appropriately experienced peer reviewer will help insure that there are no major engineering mistakes or issues overlooked and the appropriate effort has been made to develop both a safe and cost effective foundation design.

Because geotechnical engineering on which the foundation design is based is a mix of art and science, reasonable differences of opinion among geotechnical engineers based on their different experiences and training can be expected. Such potential differences can result in widely different foundation costs and performance. Appropriate peer reviews thus offer the potential to reduce both foundation costs and risks of poor foundation performance.

Sometimes projects are set up by the developer so that the peer review consultant is retained at the same time as the geotechnical design firm. Sometimes the developer will require that the geotechnical design firm have an experienced peer reviewer as part of their team, and be part of their proposal; at other times, the peer review is requested after the geotechnical design is completed.

For a peer reviewer to submit a realistic budget in his proposal, it is necessary to have a well defined scope with clarity and agreement on the goals of the peer review. The level of detail of review desired needs to be understood by both the peer reviewer and the party being reviewed as the level of detail and level of required response will affect budget estimates of both parties. A possible stage time line for peer reviews is as follows:

Concept Designs

This is the best time for value engineering discussions so that all ideas for reducing cost may be considered early in the development stage.

Subsurface Exploration and Laboratory Testing Program

Understanding and agreement on the level of effort exerted in this stage is important. There is a balance between the amount of geotechnical information (field and laboratory) that can be obtained and the selection of the maximum geotechnical design criteria for most cost effective foundation design.

Periodic Desired Team Conference Participation

It is helpful if the peer reviewer can participate in the foundation design conference meetings/workshops along with the geotechnical engineer, structural engineer and construction manager. The possible need for site trips for site conferences must be considered and the cost included if desired.

Interim Report Reviews

The peer reviewer should have the opportunity to review any interim reports or preliminary design recommendations as any questions or suggestions or disagreements can be discussed at that time with the design geotechnical firm with any modifications called for outlined in subsequent reports.

Final Report Review

If the peer reviewer has been involved in the earlier stages as outlined above, the final report review amounts to a confirmation of what has already been agreed to.

Foundation Drawings and Construction Specifications

Since at this point all parties are in agreement with the foundation design, peer review is an opportunity to make any comments for improved clarity. If the peer reviewer has particular expertise and experience with the foundation system selected, a review of draft specification permits the opportunity for making any changes that might maximize clarity.

Pile Load Test Results Review

Peer review of pile load test results may be particularly important in the event that changes in foundation design may be required. Poor results may require lengthening piles at significant cost or better than anticipated results may permit shortening piles for resulting cost savings.

Peer Review Services beyond Defined Scope

On occasion, when the peer reviewer has some particular expertise or experience that the design geotechnical engineer lacks, the peer reviewer's scope can be added to include actual design work or specification development. This happened on one of the case histories described below.

Potential Problems with Peer Review

Critics of peer review have concerns that competitive jealousies could obstruct objectivity and lead to efforts aimed primarily at enhancing ones own image and prestige rather than enhancing the project goals. Granted that this is a concern to guard against, it hopefully has not occurred on the projects in which the authors have been involved.

Case Histories and Results

Petronas Towers

Petronas Towers is a case history where the senior author had considerable involvement as a peer reviewer from early in the design stages. The design team included a local geotechnical engineering firm which also did smaller scale structural engineering. The developer retained an internationally recognized structural engineering firm (Thornton Tomasetti) for the actual structural design. A schematic profile of the towers and foundation system is shown in Figure 2. The owner defined maximum allowable differential settlement across each tower of 12mm made cost effective foundation design very difficult in light of the site geology.

Figure 1. Petronas Towers

The required tower location was immediately above a karstic limestone canyon overlain by siltstone and sandstones that had weathered to a very dense soil material. The canyon had very steep walls resulting in a relatively shallow depth to limestone on one edge of the tower (less than 50 meters) to more than 200 meters (actual depth unknown) at the center of the canyon between the two towers. The peer reviewer was involved in all stages in the investigation and design as outlined above. The peer review involved two state-side meetings with the design team and local geotechnical engineering firm and involved six trips to the site working with the local geotechnical engineering firm. Details of the investigation, design and observed performance of the structures is included in two papers listed in the references. (Baker 1994, 1998)

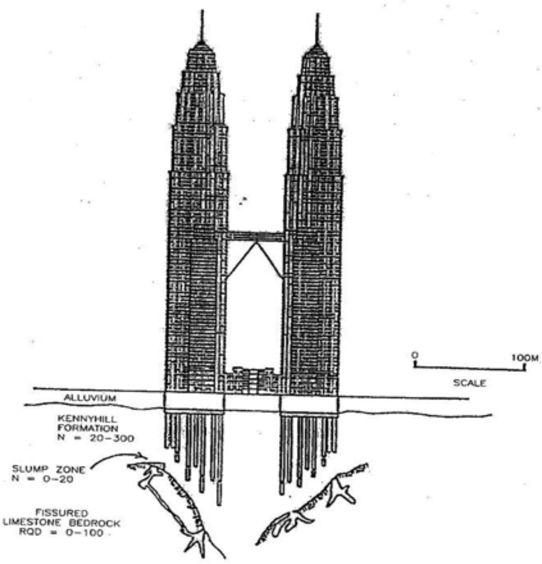

Figure 2. Tower Foundation Profile (Baker 1994, 1998)

When it became clear that a major ground improvement program would be required to make safe construction at this site feasible, and due to the limited experience of the local geotechnical firm with regard to ground improvement, the services of the peer reviewer were increased to include development of a grouting program for the required ground improvement and development of specifications for the grouting program as well as providing observation services during the six month grouting program.

This was a potential opportunity for competitive jealousies to arise but through close cooperation with the local geotechnical engineers any such controversies were avoided.

Being involved at all stages of the investigation, testing and design analysis helped develop the concept of variable length piles designed to accomplish the differential settlement criteria. The end result of the collaborative efforts of the parties involved was foundation performance that exceeded predictions with total observed settlement less than predicted and maximum differential settlement less than the required minimum of 12mm.

T & C Tower

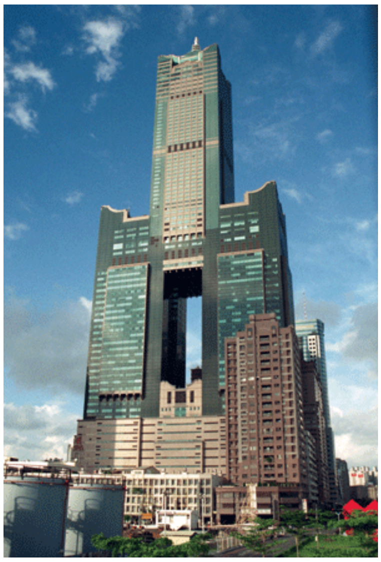

Figure 3. T & C Tower

T & C Tower in the city of Kaohsiung, Taiwan is an 85-story tower with two 40-story adjacent wings supported on a common mat on top of eight super columns, all inside a continuous 1.5 meter thick slurry wall. The support of the super columns directly under the mat was accomplished by constructing a box-shaped caisson with four walls dug with the diaphragm wall digging machine. These diaphragm wall elements (continuous barrettes) extended far enough into the underlying dense sands to carry the enormous structural loads in combination friction and end bearing and in combination with the mat. To assure adequate end bearing the sand within the box diaphragm walls was improved by jet grouting. Because of the uniqueness of the foundation system and the very high structural loads, concern was expressed to have a peer review of the planned foundation system. The peer review involved a site visit with detailed discussions with the local geotechnical engineer regarding the design and construction. The peer review was positive and the project construction continued to successful completion. In principle, because of the complexity of this project, this would have been a good case for having the peer reviewer involved from the beginning. However, the local geotechnical engineer was very experienced and competent so that the peer review as performed merely provided confirmation and assurance that the foundation design was sound.

Taipei 101

Figure 4. Taipei 101

Taipei 101, currently the tallest completed building in the world, is a case where the local geotechnical engineer (the same engineer as was involved in T & C Tower) (Dunstan Chen of Sino Geotechnology) decided to retain a peer review consultant on his own to review his foundation design and design assumptions, since the proposed building would be the world's tallest. At the time of the peer review retention, the basic foundation investigation and design concept was completed and the purpose of the peer review was to see if there was any additional information that needed to be obtained or any questions that needed to be raised and answered.. Two other peer reviewers were retained by other parties involved in the project. All these peer reviewers had questions and suggestions that were addressed in conference among the parties involved.

The foundation system as peer reviewed, designed and constructed proved more than adequate, which in combination with the structural design of the tower withstood a major earthquake during late construction of the tower.

This is another case where bringing in peer reviewers partway in the foundation design process proved effective due to the experience, knowledge and competence of the geotechnical design engineer.

Burj Dubai

Figure 5. Burj Dubai

Burj Dubai, currently under construction, will be the world's tallest building when completed. Built in an area (Dubai) where the foundations consist of a relatively soft rock of variable strength and compressibility, the design geotechnical engineer brought on board an internationally recognized consultant to participate in the foundation investigation right from the beginning. In addition, the design architect and structural engineer retained their own geotechnical peer review consultant with whom they had many years of successful experience working together. Both peer review consultants were involved from the beginning of the investigation and participated in design review conferences either by phone or in person. Major issues for review were the rock properties to use in the design friction and bearing including the rock modulus for settlement prediction, the percent of load carried by the mat, and the length of piles required for adequate bearing capacity and tolerable settlement. Full scale pile load tests were used to confirm design assumptions. Through the process of the peer reviews it was possible to reduce the pile lengths modestly at significant cost savings. The pile load tests confirmed the conservatism of the design assumptions. With more than 80 percent of the total load in place, the observed settlements are below the most optimistic predictions of both the geotechnical design engineer and both peer review consultants.

Doha Convention Center and Tower

Figure 6. Doha Convention Center and Tower

The Doha Tower, located in Qatar, is scheduled to be 550 meters tall and as such will be the world's second tallest building. Proposals were requested by the construction manager for both geotechnical engineering design services and peer review services. STS Consultants, Ltd. and their Dubai office was selected as the geotechnical engineering design consultant with a different international recognized geotechnical peer review consultant. Thus, the peer review consultant has been able to comment on the different stages of foundation investigation testing and design and is involved in most of the stages described at the beginning of the paper. We believe this review has been important and has permitted responses and modifications to be made while the project is ongoing. The foundation system is a core mat with four smaller mats supporting super columns at the corners of the core. All mats are supported on bored piles. At the time of the writing of this paper, the pile testing program has just been completed in the convention center and is in progress in the tower. Production pile installation is about to commence in the convention center portion.

Chicago High Rises

Along with New York (and now Dubai) Chicago is known as the skyscraper city where at one time the city had three of the four tallest buildings in the world. Chicago has lost its title as having the world's tallest building but is still building very tall buildings like the Trump Tower. In recent years the City has installed a peer review process which the developer actually pays for at least in part. In the geotechnical and foundation peer review section, the reviews have often been performed after the foundation investigation and geotechnical report have been submitted for final foundation design. When the peer reviewer disagrees with the geotechnical engineer at this late stage and may want additional work done, it can be embarrassing for the geotechnical engineer who has to go back to the owner or developer for additional funds and explain the required delays.

Figure 7. Trump Tower

Thus, this after-the-fact review is much less desirable than reviews which can be made early enough to be included in investigation cost projections. Efforts are now made to involve the peer reviewer at an earlier stage for his input if it should differ from the design geotechnical engineer's. Usually with the recent tall building projects, variances are required to exceed code values. This makes it even more important to involve the peer reviewer early on with the request for code variance. Currently, the potentially tallest building in North America is under construction and the City's peer reviewer has been involved (sometimes informally) almost from the beginning. This approach leads to less surprises and happier clients down the road.

Conclusions

The role of geotechnical peer review services on some of the world's tallest buildings has been discussed including the possible range of these services. Opinions on the desirable qualities of peer reviewer have also been presented. The effectiveness and potential cost savings along with increased performance assurance has been illustrated by the case histories discussed. The authors conclude that best results can be obtained if the peer reviewer is involved from the beginning of the project through the final foundation design development.

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Acknowledgements

1.+2. Petronas Towers: *Architect:* Cesar Pelli & Associates (now Pelli Clarke Pelli Architects), *Associate Architect:* Adamson Associates, *Architect of Record:* KLCC Berhad Architectural Division, *Client:* Kuala Lumpur City Centre Holdings Sendirian Berhad; Kuala Lumpur City Centre Berhad, *Structural Engineer:* Thornton-Tomasetti Engineers; Ranhill Bersekutu Sdn. Bhd., *Geotechnical Engineer:* Ranhill Bersekutu Sdn. Bhd., *Project Management Consultant:* Lehrer McGovern Malaysia, *Contractor: Tower 1:* MMC Engineering & Construction Co. Ltd.; Ho Hup Construction Sdn. Bhd.; Hazama Corporation; JA Jones Construction Co. Ltd.; Mitsubishi Corporation, *Contractor: Tower 2 and Skybridge:* Samsung Engineering & Construction Co. Ltd.; Syarikat Jasatera Sdn. Bhd. JV

3. T&C Tower: *Architect:* C.Y. Lee & Partners Architects/Planners, *Associate Architect:* HOK Architects, *Client:* Tuntex Group, *Developer:* Chien Tai Cement Corporation; Tuntex Group, *Geotechnical Engineer:* Sino Geotechnology; Construction Consulting Services, Turner International

4. Taipei 101: Architect: C.Y. Lee & Partners Architects/Planners, Client: Taipei Financial Center Corp., Structural Engineer: Thornton-Tomasetti Engineers; Evergreen Consulting Engineering, Inc., Geotechnical Engineer: Sino Geotechnology, Project Manager: Turner International SA

5. Burj Dubai: *Architect/Engineer:* Skidmore, Owings & Merrill LLP, *Local Consultant:* Hyder Consulting Middle East Ltd., *Client:* EMAAR Properties, *Contractor:* Samsung-BESIX-Arabtec, *Geotechnical Engineer:* Hyder Consulting, Ltd., *Construction Manager:* Turner Construction International

6. Doha Tower: *Architect:* Murphy/Jahn Architects, *Client:* Qatar Diar Real Estate Investment Co., *Structural Engineer:* Magnusson Klemencic in association with Hyder Consulting, *Geotechnical Engineer*: STS Consultants, Ltd., *Project Manager:* Turner International

7. Trump Tower. *ArchitectEengineers:* Skidmore, Owings & Merrill LLP, *Client:* The Trump Organization, *Geotechnical Engineer:* STS Consultants, Ltd., *Construction Manager:* Bovis Lend Lease