Title: **High-Rise Construction Risk Control Technology and Management**

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Subjects: Conservation/Restoration/Maintenance
Security/Risk

Keywords: Construction
Risk
Technology

Publication Date: 2012

Original Publication: CTBUH 2012 9th World Congress, Shanghai

Paper Type:
1. **Book chapter/Part chapter**
2. Journal paper
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

High-Rise Construction Risk Control Technology and Management

高层建筑建设风险控制的技术与管理

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Abstract

According to the characteristics of the Shanghai Tower, this paper will study construction risks in the construction process by means of WBS and RBS methods and then conclude with a list of risks and risk factors in the construction process. The study shows that there are 56 major sources of construction risks including super-deep underground projects, supertall structures, etc. Based on these major risk sources, risk control technologies, early warning signs, and emergency responses in high-rise constructions are studied further. General practice shows that risk control and management can help obtain the expected results more safely.

Keywords: Supertall Building, Construction Risks, Risk Management

摘要

根据上海中心工程的特点，采用WBS和RBS方法等对该工程建造过程中施工风险进行研究，得到了施工风险清单和风险因素。研究表明，本工程主要施工风险主要表现在超深地下工程、超高结构等方面累计重大风险源共56个，针对重大风险源进行了超高层建筑施工风险控制技术、预警与应急研究，实践表明，风险控制及管理取得了预期的效果。

关键词：超高层、施工风险、风险管理

With social and economic developments increasing, land resources are decreasing, especially in large cities where more tall buildings are being constructed. Since high-rise steel structural projects are usually located in a city's busiest areas, challenges such as complex geological environments, poor construction conditions, long construction periods, project complexities, and high-altitude operations will inevitably result in greater quantities of risk in complex categories or even an accident during the construction period which will cause great economic losses and social implications. For instance, the Shanghai World Financial Center was under construction in 2007 and had suffered from fire incidents which caused a deviation in the frame columns of the high-rise steel structure which resulted in the suspension of the project. Therefore, the risk analysis and assessment for high-rise steel structures in the construction phase plays a significant role in the whole project.

Project Overview

The Shanghai Center tower's total site area is approximately 30,368m^2 with a total building

随着社会经济的发展，土地资源尤其是大城市的土地资源越来越紧张，高层建筑也越来越多。超高层钢结构工程往往由于处于城市最繁华地段，存在地质环境复杂、施工条件差、施工周期长、工程复杂、高空作业等特点，这势必造成工程在施工期内的风险数量多、种类复杂，甚至出现事故， 造成较大的经济损失和社会影响。如2007年上海环球金融中心在施工中发生火灾事故；某超高层钢结构在施工中部分框架柱出现了施工偏差，致使该工程暂时停工。可见，对高层钢结构施工阶段风险分析与评估，意义重大。

工程概况

上海中心大厦总用地面积约30368m2，总建筑面积约574058m2，其中地上总建筑面积约410139m2。地下结构5层，地上部分包括124层塔楼和7层的东西裙房。塔楼主体高度580m，建筑总高度632m。西裙楼与主楼设置抗震缝分开，东裙楼与塔楼为一结构整体，裙楼主体结构高度约38m。塔楼竖向分为九个功能区，1区为大堂、商业、会议、餐饮区，2区至6区为办公区，7区、8区为酒店和精品办公区，9区为观光区，9区以上为屋顶皇冠。其中1至8区顶部为设备避难层。外墙采用双层玻

area of about 574,058m^2, in which, the total building area above ground is about 410,139m^2. There are five stories underground and 124 stories above ground including a seven-story podium. The main body of the tower is 580m in height with a total building height of 632m. The west podium wing is separated from the main tower building by a seismic joint, while the east podium wing and the tower are built with the structure as a whole. The main structure of the podium is about 38m high. The tower is vertically divided into nine functional zones: Zone 1 includes the lobby, retail spaces, conference rooms, and dining facilities. Zones 2 to 6 are office-based. Zone 7 and Zone 8 accommodate hotels and boutique office areas. Zone 9 acts as an observatory. The space above Zone 9 is the roof crown From Zone 1 to Zone 8, the top floors of each zone are mechanical refuge floors. The exterior wall is built with a double-layer curtain wall system, with a vertical atrium formed between the inner and outer curtain walls. The entire project construction is designed and constructed with a green sustainable development aiming to achieve a three-star rating from the China Green Building Association, as well as LEED Gold Certification.

Risk Identification

Risk identification uses a tree of fault analysis strategy. First, the main construction characteristics are summarized as follows:

- Filling pile,
- Extra-large- and extremely deep foundations,
- Extra-large and super-thick base plate concrete construction

璃幕墙，内外幕墙之间形成垂直中庭。整个工程建设贯穿绿色可持续发展理念，要求达到中国绿色建筑三星级标识和LEED金奖双认证。

风险识别

风险识别采用故障树法。首先对工程特点进行分析，本工程有以下几大施工特点：

- 灌注桩；
- 超大超深基坑；
- 超大超厚大底板混凝土施工；
- 超高混凝土施工；
- 钢结构重大，施工大；
- 巨型桁架结构庞大，施工制作及安装难度大；
- 幕墙钢撑大量悬挑，精细吊装实施难；
- 外幕墙建筑立面收分旋转，板块分格及制作安装精度控制难度大。
- 结构超高，施工措施用设备选择、设计及管理难度大；
- 结构超高，立体交叉施工多，安全风险高。

针对各项主要施工内容的风险事件及风险因素的识别详见表1~表6。

Risk Event 风险事件	Significant Risk Factors	重要风险因素
Degree of vertical deviation pile 成桩垂直度偏差	1. Construction site is not flat, not solid; stent endurance is not enough, the occurrence of differential settlement, resulting in the drill pipe not being vertical. 2. Severe wear of drilling rig components, the connector is loose, drill pipe bending, deformation, resulting in the drill pipe joints not being able to be straight, drill shaking deviates from the axis and reaming will be enlarged. 3. In case of groundwater obstructions or the soft and hard soil junction the drill may meet uneven resistance, causing the drill bit to come off course.	1. 施工场地不平整，不坚实；支架承受力不够，发生不均匀沉降，导致钻杆不垂直。 2. 钻机部件磨损严重，接头松动钻杆弯曲，变形，造成钻杆接头间不顺直，钻头晃动偏离轴线，扩孔较大。 3. 遇有地下水障碍物或软硬土层交接处钻头受阻力不均匀，造成钻头偏离方向。
Broken Pile 断桩	1. The concrete slump being too small, too much aggregate and poor concrete workability resulting in catheter blockage; after clean up of the pipe the concrete pouring could easily lead to a broken pile. 2. When the catheter moves up, it comes out of the concrete pouring surface to enhance continue pouring concrete,the middle of the formation of folder mud layer. 3. Leaking of the pipe joints will lead to mud penetratation into the catheter mixed with the concrete. 4. Concrete supply is interrupted. If not continuous pouring the catheter may be blocked.	1. 砼坍落度太小，骨料太大，砼和易性较差造成导管堵塞；在排堵后再浇砼易造成断桩。 2. 导管提升时导管脱离已浇砼面后继续浇筑砼时，中间形成夹泥层。 3. 导管接头处渗漏，使泥浆渗入导管混入砼中。 4. 砼供应中断，不能连续浇筑时，造成导管堵管。
Hole collapse 坍孔	1. The bottom of the casing and the surrounding clay fill is not compacted, the depth of the casing is not enough and the casing is in a permeable sandy layer. 2. Water level in the hole is not high enough and water pressure can not balance. 3. When tidal drilling or drilling through strong permeable layer, water supplement is not strong enough to cause the changes of water levelin the hole. 4. If found that there is high pressure of water in the hole, it will lead to the foundry at the bottom of the hole and the hole wall collapse. 5. Influenced by vibration near the drilling hole and with a mud weight ratio that is too small, may result in a sub-standard viscosity. 6. Hole forming too fast the hole walls cannot form a layer of mud wrap. 7. When dipping the steel reinforcement cage it accidently touches the jack wall and destroys the formation of the hole wall mud wrap. 8. Timely pour of the concrete, but when the hole is finished, pause for too long.	1. 护筒底部及四周粘土填入未夯实，护筒深度不够及护筒埋设在砂类透水层中。 2. 孔内水位高度不够，水头压力不能达到平衡。 3. 钻孔时潮水涨落或钻经强透水层时，水源补足不够引起孔内水位变动。 4. 孔中发现强承压水导致孔底翻砂及孔壁坍塌。 5. 受钻孔附近振动影响及泥浆比重偏小粘度不合标准。 6. 成孔速度过快，孔壁上未形成泥膜。 7. 吊放钢筋笼时碰插孔壁，破坏已形成的孔壁泥膜。 8. 成孔后未及时浇灌砼，停顿时间过久。
Plugging pipe 堵管	1. Concrete aggregate graduation unreasonable. 2. Too long time for pouring concrete (mechanical fault and other reasons). 3. Catheter is not well sealed, part of it leaks. 4. Catheter depth is too long. 5. Too long to use the prepared concrete. 6. Mechanical fault.	1. 混凝土骨料级配不合理。 2. 混凝土灌注时间过长（机械故障等原因）。 3. 导管密封不良，局部漏水。 4. 导管埋深过长。 5. 混凝土出场时间过长。 6. 机械故障原因。

Table 1. List of significant risk factors: ultra-deep caisson pile.
表1. 重要风险因素清单：超深钻孔灌注桩

Risk Event 风险事件	Significant Risk Factors	重要风险因素
Deformation or collapse of the guide wall 导墙变形或塌陷	1. Lack of guide wall strength or stiffness 2. The guide wall of the foundations collapsed or eroded 3. The inside of the guide wall are not set support 4. Overloaded on the role of the guide wall(trenching machines, cranes, steel cage)	1、导墙强度或刚度不足； 2、导墙的地基发生坍塌或收到冲刷； 3、导墙内侧未设置支撑； 4、作用在导墙上的荷载（挖槽机、起重机、钢筋笼）过大。
The collapse of tank wall 槽壁塌陷	1. The slurry surface reduces in the tank during the trench process beyond the scope of safety 2. Mud of inferior quality 3. Due to rainfall, under ground water level rises sharply resulting in the slurry level increasing beyond the range 4. Under ground water flows too fast for mud to form a mud skin on the surface of the groove wall 5. There are underground obstacles 6. There is a very weak powder soil or loose sands layer 7. Due to the loads of the upper part of the adjacent buildings or bulldozers, the side wall of tank is pressed by the lateral earth pressure 8. Cranes, etc are too close to the trenching location, ground load is too heavy.	1、成槽过程中槽内泥浆液面降低，超过了安全范围； 2、泥浆质量不合格； 3、由于降雨等原因，地下水位急剧上升导致泥浆液面上升超过范围； 4、地下水的流速过大，泥浆不能在槽壁面上形成泥皮； 5、存在地下障碍物； 6、存在极软弱的粉土层或松砂层； 7、在相邻建筑物或堆土等上部荷载作用下，槽壁受到侧向土压力； 8、吊塔等过于靠近挖槽位置，地面荷载过大。
Trenching equipment stuck in the slot 挖槽机具卡在槽内	1. Trenching equipment stays on the tank, sludge deposition occurs in the mud around the trenching equipment, makes trenching equipment hard to remove 2. When the digging machine in the clay or the skin of mud walls are too thick, the trenching equipment can easily become stuck in the slot on the side of it 3. The devaition of trench direction remains too much (hold bending) 4. A large piece of stone falling into the tank or underground obstacles cause the trenching equipment to get stuck	1、挖槽机具留放在槽内，泥浆中所悬浮的泥渣沉积任挖槽机具周围，使挖槽机具不易提出； 2、当在粘土层内挖机或者壁面上泥皮很厚时，挖槽机具的侧面就很容易被槽壁夹住； 3、挖槽方向的偏差过大(孔弯曲)； 4、大块石落入槽内或地下障碍物等卡住挖槽机具。
Deformation or damage of the reinforcement cage 钢筋笼变形或破坏	When reinforcement cage is hung into the tank the location of the sling device can be destroyed, the joints of the reinforcement cage lost and the reinforcement cage deformed upon lifting	主要是钢筋笼在吊入槽内时吊索装置的位置发生破坏、钢筋笼接头部位脱落以及钢筋笼起吊时产生变形。
Difficulties of locating the reinforcement cage 钢筋笼下放困难	1. The uneven surfaces of the groove wall 2. The sediment remains at the bottom of the trench 3. Reinforcement cage longitudinal bending joints and steel cage positioned protruding too much	1、槽壁面的凹凸不平； 2、槽底有沉渣； 3、钢筋笼纵向接头弯曲及钢筋笼定位块过于凸出等。
Inadequate density of walls 墙身密密实度不足	1. Pipe blockage 2. Extubation too fast 3. The depth of conduit buried in concrete does not meet the requirements	1、堵管； 2、导管拔管过快； 3、导管埋入混凝土深度不符合要求。
Reinforced cage floating up 钢筋笼上浮	1. The reinforcement cages floats up during the process of concreting is often due to too much sediment at the bottom 2. Conduit buried too deep or pouring concrete too fast; 3. When the weight of the reinforcement cage is too light it will float up	1、钢筋笼上浮在混凝土浇灌过程中发生钢筋笼上浮，常是由于槽底沉渣过多； 2、导管埋人深度过大，或浇注混凝土速度过快而引起； 3、当钢筋笼重量太轻也会发生上浮现象。
Unit groove segment joints leaking 单元槽段接头漏水	1. V steel not properly scrubbing the surface 2. Deviations in the position of the reinforcement cage location 3. Flow around	1、V型钢板刷壁不到位； 2、钢筋笼下放位置有偏差； 3、绕流。
Pit collapse 基坑塌陷	1. Envelope all related scope of the strata, survey data are not detailed or inaccurate 2. Inappropriate choice of deep foundation pit support program 3. Containment system construction is inappropriate leading to the supporting structure deformation	1、围护所涉及范围的地层，勘察资料不详细、不准确； 2、深基坑支护方案的选择不当； 3、围护系统施工不合理，导致支护结构变形过大。
Retaining structure instability 围护结构失稳	1. Enclosure surrounded by large previously unknown holes 2. Deformations in the retaining structure are too great to support the branch point locations, and is not properly connected 3. Poor retaining structure construction quality, the structure which put into the soil is too shallow, not stiff enough and not strong enough 4. A large range of water leakage 5. The bottom of the pit suffers from the soil piping, quicksand or a large area of uplift	1、围护周边有较大未探明孔洞； 2、围护设计结构变形过大，支撑支点数、位置及连接不当； 3、围护施工质量差，围护插入土体内深度较浅，刚度、强度不够； 4、周边出现大范围漏水现象； 5、坑底土体发生管涌、流砂或大面积隆起。
Surrounding buildings deformation 周边建筑变形	1. Foundation pit design is inappropriate 2. Poor quality of foundation pit, with the earth excavation the soil displacement with the depth 3. Poor foundation pit sealing effect, the inner pit water level reduces causes the outer water level to fall as well 4. Earth excavation method is incorrectly chosen	1、基坑围护设计不合理； 2、基坑围护施工质量差，随着土方开挖，土体深部位移量较大； 3、基坑围护止水效果差，坑内降水导致坑外水位随之下降； 4、土方开挖方法选择不当。
Uplift of the bottom of the pit 坑底隆起	1. The retaining structure is not deep enough 2. The quantity of uplift piles is too few or has a poor construction quality	1、围护结构插入土体的深度不够； 2、抗拔桩数量偏少或施工质量差。
Disturbance to the bottom of the foundation 基底扰动	1. Construction unit fails to follow the design and specification requirements to construct, soil height remains insufficient 2. Digging machine rolling back and forth	1、施工单位未按设计及规范要求进行要求进行施工，坑底留土高度不够； 2、挖机来回碾压。
Too high or too low water level in the foundation 基坑水位偏高或过低	1. Rainfall is well above normal, pumping capacity below normal level, resulting water level in the pit is high; 2. Pumping interval is too long or too short.	1、降水井数量偏少，抽水能力偏低，导致坑内水位偏高； 2、抽水间隔时间过长或过短。

Table 2. List of significant risk factors: a large ultra-deep foundation pit (the main building follows to be built)
表2. 重要风险因素清单：超大超深基坑(主楼顺做)

- Super-high concrete construction,
- Large-scale steel structure and construction,
- High level of difficulty in mega truss construction and installation,
- Difficulties with refined and precise implementation of the curtain wall cantilever steel support,
- Difficulties in controlling convex façade curtain wall rotations and precise production, installation, and manufacturing of sub-grid plates
- Difficulties in equipment selection, design, and management of the facilities used in construction due to the supertall structure,
- Too many interchangeable construction elements and high security risks due to the supertall structure.

Identified risk events and risk factors for the main construction are highlighted in Tables 1–6.

Risk Evaluations

A vague comprehensive evaluation method is applied to calculate the membership grades and weigh the evaluation indicators in order to make the results more unbiased.

风险评估

采用模糊综合评价方法进行评估，该方法是将评价指标的隶属度与权重进行模糊运算使计算结果更显客观。

评价指标权重的确定

权重的确定是采用层次分析法，将同级各个因子两两相互比较，并按九标度表(见表7)规则进行仿数量化后构成一个构造判断矩阵，该矩阵经过一致性检验后其最大特征值对应的向量为对应各因子的权重向量。

该矩阵在一致性检验后，其最大特征值向量为对应风险事件的权重向量 $W=[w_1 \ldots w_n]$，具体计算步骤如下：

1. 计算判断矩阵的最大特征根

$$\lambda_{\max}: \quad \lambda_{\max}=\frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i}$$

式中：

λ_{max}—判断矩阵的最大特征根；

n — 判断矩阵的行数；

A — 判断矩阵；

Risk Event 风险事件	Significant Risk Factors	重要风险因素
Vertical steel columns do not meet the requirements 钢立柱垂直度不符合要求	1. Decentralization of steel pipe column verticality control 2. Bored Pile Wall and steel pipe backfill graded sand and gravel, and fixed steel pipe column.	1. 钢管柱下放垂直度控制； 2. 钻孔桩护壁与钢管之间回填级配砂石，固定好钢管柱。
Floor walls and column pile sedimentation differences control 地连墙、立柱桩沉降差异控制	1. Pile grinding resistance 2. The bottom of the pit uplift 3. Individual column pile and diaphragm wall deposition is too much 4. Column pile bearing capacity 5. Working conditions are unreasonable	1. 桩摩阻力； 2. 坑底隆起； 3. 个别立柱桩及地下墙沉降过大； 4. 立柱桩的承载力； 5. 工况安排不合理。
Floor walls leaking 地连墙渗水	1. V steel not properly scrubbing the surface 2. Deviations in the position of the reinforcement cage location 3. Flow around	1. V型钢板刷壁不到位； 2. 钢筋笼下放位置有偏差； 3. 绕流。
The lateral deformation of floor wall is too great 地连墙侧向变形过大	1. Support is not promptly created 2. Earthwork excavation does not meet the requirements 3. Working conditions are unreasonable	1. 支撑未及时形成； 2. 土方开挖方式未按施组要求； 3. 工况安排不合理。
Surrounding buildings deformation 周边建筑物变形	1. Foundation pit design is inappropriate 2. Poor quality of foundation pit, with the earth excavation the soil displacement with the depth 3. Poor foundation pit sealing effect, the inner pit water level reduces causes the outer water level to fall as well 4. Earth excavation method is incorrectly chosen 5. Earth excavation is not the construction of information technology 6. Support for the cushion layer is not formed in a timely manner.	1. 基坑围护设计不合理； 2. 基坑围护施工质量差，随着土方开挖，土体深部位移量较大； 3. 基坑围护止水效果差，坑内降水导致坑外水位随之下降； 4. 土方开挖方法选择不当； 5. 土方开挖未实现信息化施工； 6. 支撑、垫层未及时形成。
Deformation in the main building 主楼变形	1. Earth excavation method is incorrectly chosen 2. Hierarchical segmentation inappropriate 3. Earth excavation is not the construction of information technology 4. Support for the cushion layer is not formed in a timely manner.	1. 土方开挖方法选择不当； 2. 分层分段不合理； 3. 土方开挖未实现信息化施工； 4. 支撑、垫层未及时形成。
Floor wall and main structure nodes 地连墙与主体结构节点	Embedded reinforcment deviates position	预埋钢筋位置偏差
Steel pipe columns and slab nodes 钢管柱与梁板节点	1. Pre-welded shear hoop positioning accuracy does not meet the requirements 2. Column pile settlement, elevation changes occur	1. 预焊接抗剪环箍定位精度不符合要求 2. 立柱桩因沉降，标高发生改动
Wall and floor connection node 墙与底板连接节点	1. Node junction integrity is not enough 2. The node's water resistance does not meet the requirements	1. 节点连接处整体性不够； 2. 节点防水性不符合要求

Table 3. List of significant risk factors: podium pit inverse built
表3. 重要风险因素清单：裙房基坑逆作

Risk Event 风险事件	Significant Risk Factors	重要风险因素
Truss layer connection misplaced 桁架层连接错位	1. The production accuracy of components deviates too much (Assembly accuracy deviation is too great, welding deformation is too great) 2. Component misalignment too great (component assembly positioning deviates too much; welding deformation is too great)	1、构件制作偏差过大（组装精度偏差过大、焊接变形过大） 2、构件安装偏差过大（构件组装定位偏差过大；焊接变形过大）
Lamellar tearing of Steel Plate 钢板层状撕裂	1. Steel plate does not meet the requirements 2. Unreasonable welded joints	1、钢板材质不符合要求 2、焊接接头不合理
Slab delayed crack 厚板延迟裂纹	Unreasonable welding process	焊接工艺不合理

Table 4. List of important risk factors: the main structure
表4. 重要风险因素清单：主体结构

Risk Event 风险事件	Significant Risk Factors	重要风险因素
Deviation in the mounting dimensions is too great 安装尺寸偏差过大	1. Deviation in the size of the curtain wall supporting structure is too great 2. Component installation measurement and control is inappropriate	1. 幕墙支撑制作尺寸偏差过大 2. 构件安装测量控制不到位

Table 5. List of risk factors: supporting steel for the curtain wall
表5. 重要风险因素清单：幕墙支撑钢结构

Risk Event 风险事件	Significant Risk Factors	重要风险因素
The curtain plate cannot be installed 幕墙板块安装不上	1. The precision of the curtain wall plate products does not meet the requirements 2. The design of curtain wall connection node is unreasonable. Does not have three-dimensional adjustment function 3. The measurement positioning of the curtain wall connection is inaccurate 4. Curtain wall supporting steel structure deformation is too great 5. Does not meet the requirements of the curtain wall plate installation accuracy	1、幕墙板块制作精度不符合要求 2、幕墙连接节点设计不合理，不具备三维调节功能 3、幕墙连接测量定位不准 4、幕墙支撑钢结构变形过大 5、幕墙板块安装精度不符合要求

Table 6. List ist of risk factors: curtain wall structure
表6. 重要风险因素清单：幕墙结构

Scale 标度	Meaning	含 义
1	Demonstrates that of the two factors compared, they have the same importance	表示两个因素相比，具有相同重要性
3	Demonstrates that of the two factors compared, the former is slightly more important than the latter	表示两个因素相比，前者比后者稍重要
5	Demonstrates that of the two factors compared, the former is significantly more important than the latter	表示两个因素相比，前者比后者明显重要
7	Demonstrates that of the two factors compared, the former is very much more important than the latter	表示两个因素相比，前者比后者强烈重要
9	Demonstrates that of the two factors compared, the former is extremely more important than the latter	表示两个因素相比，前者比后者极端重要
2, 4, 6, 8	Demonstrates intermediate values in the above	表示上述相邻判断的中间值
Reciprocal 倒数	If factor y_1 and factor y_i the importance ratio is a_{ij}, then the importance ratio is a_{jr} between y_i and y_r	若因素 y_1 与因素 y_i 的重要性之比为 a_{ij}, 那么因素 y_i 与因素 y_r 重要性之比为 a_{jr}

Table 7. List of important risk factors: the main structure
表7. 重要风险因素清单：主体结构

n	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54	1.56	1.58	1.59

Table 8. The average consistency index value RI
表8. 平均一致性指标 RI 值

Value 估值	Description 描述
1	Can be ignored 可以忽略
2	Worth considering 值得考虑
3	Serious 严重
4	Extremely serious 极其严重
5	Catastrophic 灾难性

Table 9. Risk estimates of the consequences C
表9. 风险影响后果C的估算方法

Ratio 概率	Value 估值	Frequency of occurrence 发生频率	Explain 说明
Rare 罕见的	1	<0.0003	The risk is extremely rare 风险极难出现一次
Occasionally 偶见的	2	0.0003~0.003	Risk does not generally occur 风险不大会出现
Possible 可能的	3	0.003~0.03	The risk may occur 风险可能会出现
Expected 预期的	4	0.03~0.3	The risk may occur more than once 风险会不止一次的发生
Frequent 频繁的	5	>0.3	The risk will frequently occur 风险会频繁发生

Table 10. Risk estimates of the consequences C
表10. 风险影响后果C的估算方法

Determination of the Evaluation Directory Significance

The weight of the importance is determined by an analytic hierarchy process which compares factors in the same level with a judgment matrix by simulating the numbers according to nine different scales (See Table 7). After a consistency check, the largest eigenvalue vector of the matrix corresponds to each factor of the weight vector.

After the consistency check, the largest eigenvalue vector is $W = [w_i \ \dots \ w_n]$ which corresponds to the weight vector of a risk event while the specific calculation steps are as follows:

1. Calculating the judgment matrix's largest characteristic root λ_{max}:

$$\lambda_{max}: \ \lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i}$$

In the formula:

λ_{max} is the judgment matrix's largest characteristic root;

n – The number of rows of the judgement matrix;

A – Judgement matrix;

W – the Judgement matrix's eigenvector;

$(AW)_i$ – Judgment matrix A and the eigenvectors of the matrix W multiplied together is the i-th element of vector AW.

2. The formula for the consistency check is: $CR = CI/RI$

In formula $CI = (\lambda_{max} - n)/(n-1)$ is the average random consistency index, when $CR \leq 0.10$. If the judgment matrix does not satisfy the consistency then it should be adjusted. The value of the average consistency index is outlined in Table 8.

Determining Risk Subordination Levels

The calculation of risk events for the level of subordination uses the expert evaluation method to determine the estimated values for the sequence C first, and then the occurrence of the probability P of each risk event. Afterwards, the value of P multiplied by C will be applied to obtain the risk event for the risk subordination level from the subordination function.

To determine the consequence C of the risk event. The expert evaluation method is used to determine the consequence of risk events. This evaluation method is outlined in Table 9.

To determine the occurrence probability P of the risk. Risk event occurrence probability is divided into five grades. This is shown in Table 10.

To determine the subordination function. The risk level is divided into five grades; there are "first class risks", "second class risks", "third class

Risk Level 风险水平	Membership Function 隶属函数
1st class risk 1级风险	$r_{i1} = \begin{cases} 1 & 0 < x \leq 2 \\ 3-x & 2 < x \leq 3 \\ 0 & x > 3 \end{cases}$
2nd class risk 2级风险	$r_{i2} = \begin{cases} x-2 & 2 \leq x < 3 \\ 1 & 3 \leq x \leq 4 \\ 5-x & 4 < x \leq 5 \\ x-5 & 5 < x < 6 \\ \frac{8-x}{2} & 6 < x \leq 8 \\ 0 & x < 2 or x > 8 \end{cases}$ $r_{i2} = \begin{cases} x-2 & 2 \leq x < 3 \\ 1 & 3 \leq x \leq 4 \\ 5-x & 4 < x \leq 5 \\ x-5 & 5 < x \leq 6 \\ \frac{8-x}{2} & 6 < x \leq 8 \\ 0 & x < 2 \text{或} x > 8 \end{cases}$
3rd class risk 3级风险	$r_{i3} = \begin{cases} x-4 & 4 \leq x < 5 \\ 6-x & 5 \leq x < 6 \\ \frac{x-6}{2} & 6 \leq x < 8 \\ 1 & 8 \leq x \leq 12 \\ \frac{15-x}{3} & 12 < x \leq 15 \\ 0 & x < 4 or x > 15 \end{cases}$ $r_{i3} = \begin{cases} x-4 & 4 \leq x < 5 \\ 6-x & 5 \leq x < 6 \\ \frac{x-6}{2} & 6 \leq x < 8 \\ 1 & 8 \leq x \leq 12 \\ \frac{15-x}{3} & 12 < x \leq 15 \\ 0 & x < 4 \text{或} x > 15 \end{cases}$
4th class risk 4级风险	$r_{i4} = \begin{cases} \frac{x-12}{3} & 12 \leq x < 15 \\ 1 & 15 \leq x \leq 20 \\ \frac{25-x}{5} & 20 \leq x < 25 \\ 0 & x < 12 \end{cases}$
5th class risk 5级风险	$r_{i5} = \begin{cases} \frac{x-20}{5} & 20 \leq x \leq 25 \\ 0 & x < 20 \end{cases}$

Table 11. Membership Function
表11. 隶属函数表达式

W —判断矩阵的特征向量;

$(AW)_i$ —判断矩阵A与其特征向量W相乘而得的向量AW的第i个元素。

2. 一致性检验，计算公式为：$CR = CI/RI$

其中 $CI = (\lambda_{max} - n)/(n-1)$，$RI$ 为平均随机一致性指标，当 $CR \leq 0.10$。判断矩阵具有满意的一致性，否则应予以调整。平均一致性指标 RI 值见表 8。

风险等级隶属度的确定

风险事件对于风险水平的隶属度的计算首先是采用专家打分法来确定每个风险事件的影响后果C的估值及发生概率P的估值，将P×C的值带入风险事件对于风险水平的隶属函数，便可得到风险事件对于风险水平的隶属度。

确定风险事件的影响后果C 。 采用专家调查法确定风险事件的影响后果，估值方法如表9 。

确定风险事件影响后果对应的概率P 。 风险事件的发生概率分为五个等级，估算方法如表10。

隶属函数的确定 。 将风险水平分为五个等级，分别为“1级风险”，“2级风险”，“3级风险”，“4级风险”，“5级风险”，隶属函数rij(x)见表11和图1。

风险事件隶属度值的确定。 将P*C值代入隶属函数，可得到该风险事件对五个等级的隶属向量 R_i。

risks", "fourth class risks," and "fifth class risks". The membership function rij(x) is shown in Table 11 and Figure 1.

Determination of Risk Event Subordination Level Values. By substituting the value of P*C into the subordination function, the subordination vector can be obtained in the five levels corresponding to the risk event.

Risk Acceptance Criteria

- 5th class risk: a very high level of risk. The consequences of such an accident are catastrophic and would have adverse impact on the society and politics. The acceptance criteria are: completely unacceptable, should be immediately ruled out.
- 4th class risk: A higher level of risk. The consequences of such an accident are very serious and may cause damage and casualties in a wider range of the project. The acceptance criteria are: unacceptable, should take effective control measures immediately.
- 3rd class risk: A normal level of risk. The consequences of such an accident are minor and may result in destruction in a smaller range of the project. The acceptance criteria are: do not wish to happen. The risk of loss and risk control costs can be balanced when appropriate control measures are taken.
- 2nd class risk: A lower level of risk. The consequences of such accidents can be ignored under certain conditions and does not cause major damages to the project, personnel, equipment, etc. The acceptance criteria are: allowable under certain conditions, but it must be monitored to avoid the risk increasing.
- 1st class risk: the lowest level of risk. The consequences of such accidents can be ignored and only causes extremely minor damages to the project itself, personnel, equipment, etc.. The acceptance criteria are: allowable, but should try to maintain the current level and status of risk.

Determining the Risk Level

The maximum eigenvector w_i is multiplied by the subordination level R_i results in $R'_i = w_i \cdot R_i$ (3-2).

According to the principle of maximum subordination level, the sequence quantity where the largest factor of vector, R'_i, is located is also the level of the risk. Based on the principle of maximum subordination, the level of risk is a second class risk.

The Risk of Pre-Control Methods

According to the risk assessment criteria for the risk levels of different risk events, appropriate risk control measures should be established. Due to the constraints in the length of this paper, it cannot list all the risk pre-control measures one by one.

Summary

The risk assessment of high-rise steel structural engineering can be first classified in accordance with construction goals and then an identification analysis will be processed on every category of the potential risk events using a tree of fault analysis method. The risks will be evaluated by an ambiguous comprehensive evaluation method.

Based on risk assessment and pre-established control measures, together with the risk survey in the actual project, we can reduce the risk possibility or minimize the risk of loss. Since the Shanghai Tower

Figure 1. Shanghai Tower
图1. 上海中心大厦

风险接受准则

- 5级风险：风险水平等级高，风险事故后果是灾难性的，并造成恶劣社会影响和政治影响。接受准则为：完全不可接受，应立即排除；
- 4级风险：风险水平较高，风险事故后果很严重，可能在较大范围内对工程造成破坏并有人员伤亡。接受准则为：不可接受，应立即采取有效的控制措施；
- 3级风险：风险水平一般，风险事故后果较轻微，对工程可能造成破坏的范围较小。接受准则为：不希望发生，可均衡风险损失与风险控制成本采取适当的控制措施；
- 2级风险：风险水平较低的等级，风险事故后果在一定条件下可以忽略，对工程本身以及人员、设备等不会造成较大损失。接受准则为：允许在一定条件下发生，但必须对其进行监控并避免其风险升级；
- 1级风险：风险水平最低的等级，风险事故后果可以忽略，对工程本身以及人员、设备等造成的损失极小。接受准则为：允许发生，但应尽量保持当前风险水平和状态。

风险等级的确定

将上述已经得出最大特征向量 w_i 与隶属度 R_i 相乘，即

$R'_i = w_i \cdot R_i$ (3-2)

根据最大隶属原则，由 R'_i 向量最大元素所在的列数即为该风险的风险等级。

根据最大隶属原则可知:风险等级为2级 。

风险预控措施

根据风险评估准则及各风险事件的风险等级，制定相应的风险预控措施。限于篇幅所限，本文不对各项风险预控措施一一列出。

has begun construction, it has reached about 60 floors in height, with the external steel structure reaching a height of more than 40m. During the whole process, due to the participation of construction parties continuing to enhance risk awareness and taking appropriate control measures, the project has not been a great risk event yet while some potential risks are avoided by timely risk pre-control measures.

小结

对超高层钢结构工程风险评估时可按照建设目标首先进行分类，针对每一类别确定风险事件，然后采用故樟树方法对风险进行分析识别，采用模糊综合评价方法对风险进行了评价。

根据风险评估结果及预先制定的控制措施，并在实际工程中进行风险查勘，能够把风险概率降低或把风险损失减到最少。上海中心大厦开工至今，已经施工到60层左右，外围钢结构也达到40多m的高度，由于过程中参建各方不断增强风险意识并采取了相应的控制措施，工程至今没有发生过大的风险事件，一些风险隐患也由于采取了及时的风险预控措施而避免。