Field Investigation on Industrial Buildings in Mianyang District and Some Advices on Post-earthquake Rehabilitation and Seismic Design

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ABSTRACT :

The 5.12 Wenchuan Earthquake has caused a huge loss to the lives of Sichuan people and their properties. Immediately after the earthquake, the Ministry of Industry and Information Technology of the People's Republic of China sent an earthquake loss investigation team to arrive at the five regions heavily hit by the earthquake, namely Chengdu, Deyang, Mianyang, Guangyuan and Yaan, etc., to investigate the damages to industrial buildings and equipment as well as the loss of human lives. This paper only deals with the damages to the industrial buildings caused by this earthquake, which also includes the post-quake reinforcement and retrofitting proposals as well as advices on the seismic design of industrial buildings to be built in this region in the future.

KEYWORDS: Field Damage Investigation; Industrial Buildings; Post-earthquake Rehabilitation

1. OVERVIEW OF DAMAGE TO INDUSTRIAL BUILDINGS IN MIANYANG CITY CAUSED BY THE EARTHQUKE

With a jurisdiction over two districts, one city and six counties and a total area of 20,000km2 and a population of 5.29 million, Mianyang City features six major industrial sectors such as electronics and information, metallurgy, automobile and auto part, building material, bio-pharmacy and foodstuff as well as textile, etc. Some 789 enterprises of a certain scale were investigated, whose total area of plant buildings was 12.455 million square meters. In this strong earthquake occurred in Wenchuan, area of collapsed plant buildings amounted to 1.558 million square meters, accounting for 12.5% of the total area; area of plant buildings that have been damaged but can be reinforced and rehabilitated amounted to 8.48 million square meters, accounting for 68.1% of the total area.

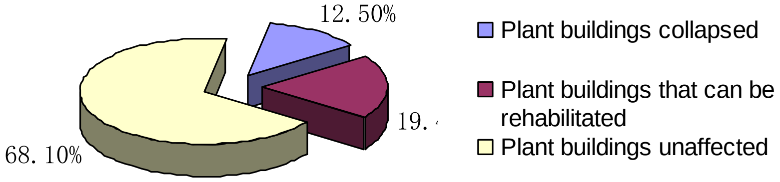

Figure 1 Degree of impact on industrial buildings in Mianyang City by Wenchuan Earthquake

Looking from the degree of damage to the industrial plant buildings in Mianyang City by Wenchuan

Earthquake, regions sufferred severe damage include four counties and cities, which are Beichuan, Pingwu, Anxian and Jiangyou. Total area of plant buildings collapsed in these four counties and cities accounts for 70% of the total area of collapsed plant buildings in Mianyang City, and the area of damage accounts for 57%. Details of these counties and cities in which the industrial buildings suffered severe damage are shown in the following figures:

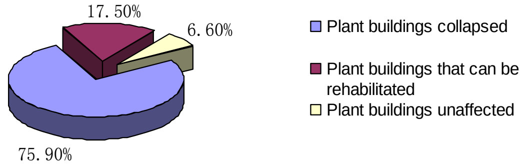

Figure 2 Degree of impact on industrial buildings in Beichuan County by Wenchuan Earthquake

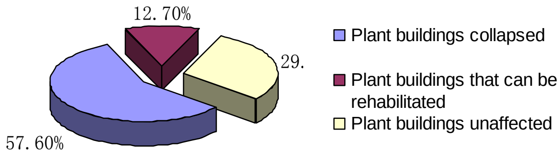

Figure 3 Degree of impact on industrial buildings in Pingwu County by Wenchuan Earthquake

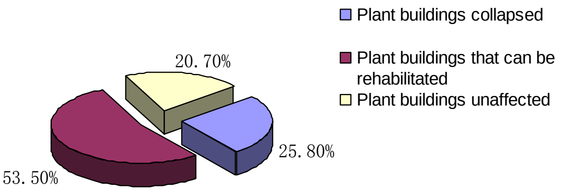

Figure 4 Degree of impact on industrial buildings in Anxian County by Wenchuan Earthquake

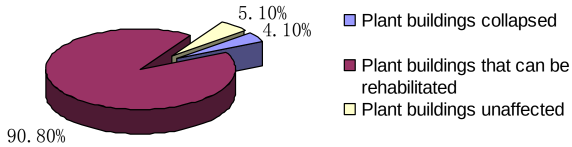

Figure 5 Degree of impact on industrial buildings in Jiangyou City by Wenchuan Earthquake

2. TYPICAL EARTHQUAKE DAMAGE TO INDUSTRIAL BUILDINGS IN MIANYANG REGION AS WELL AS THEIR CHARACTERISTRICS

2.1. Typical Earthquake Damage To Industrial Buildings In Mianyang City

2.1.1. Plant Buildings

According to the earthquake intensity distribution map of 5.12 Wenchuan Earthquake disclosed by US Geological Survey (USGS), the earthquake intensity in Mianyang City was 8 degrees, of which the earthquake intensity in Beichuan County was 11 degrees, that in Jiangyou City was nearly 9 degrees, which were far higher than the intensities specified in the seismic zonation of China, with the intensity about 3 degrees higher on average.

Buildings suffered severe damage are plant buildings of brick-concrete masonry structure which were built in the early years with lower seismic fortification level and had no concrete ring-beams and structural pillars. Buildings suffered medium-degree damage are mostly the ones of brick-concrete masonry structure and frame structure, and the damaged portions are mainly non-bearing cladding structures. Partition walls damaged are mostly because they were not properly tied with the principal structures, which have no structural safety hazard. After demolished and rebuilt, the damaged partition walls can still be used. Buildings slightly damaged or almost intact are mainly the ones of frame-shear and shear-wall structures, which were newly built in recent years according to the codes of 1989 and 2001.

2.1.1.1. Plant Buildings With Brick Columns

Plant buildings with brick columns were mostly built in the 60's and 70's of last century, most of which had no ring-beams and structural columns. These buildings are partially or completely collapsed in this earthquake, suffering the most severe damage. See Fig. 6 to 10.

Fig. 6 Gable masonry of plant buildings with ring-beams partially collapsed

Fig. 7 Gable masonry of plant buildings without ring-beams almost completely collapsed

Fig. 8 Masonry cracks at the door opening have been reinforced with steel frame

Fig. 9 Masonry at door opening with rain shed cracked

Fig. 10 Protrusion of the skylight of the plant building cracked horizontally

Fig. 11 Bent gable of the plant building completely collapsed

2.1.1.2. Plant Buildings With Bent Gables

Due to a lack of necessary tie between the bent gable of the plant building and the principal structure, the gable shifted outside under the action of the earthquake and completely collapsed. In this earthquake, a number of injuries and casualties occurred due to collapse of exterior walls. See Fig.11

2.1.1.3. Plant Buildings Of Frame Structure

Staircases of plant buildings of frame structure suffered severe damage, and the walls between windows had X-shaped shearing cracks. However, the principal structure designed according to relevant codes was mostly not damaged or collapsed, though a small number of cracks existed partially in the beam pillars.

① Staircase

Fig.12 Stair carriage broken

Fig.13 Stair girder, pillar damaged

Fig.14 Stair partition wall totally collapsed

② Wall between windows and between doors

Fig.15 Masonries of partition walls at door openings have X-shaped shearing cracks

Fig.16 Masonries of partition walls at windows openings have X-shaped shearing cracks

2.1.1.4. Plant Buildings of Gantry Steel Frame and Light-weighted Steel Structure

Principal part of all plant buildings of gantry steel frame and light-weighted steel structure investigated in Mianyang City are almost in perfect condition. Their cladding structures were also not damaged. Shown in the following pictures is a plant building with about 60m span of a printing house in Nongke District, Mianyang City, which were not damaged at all. However, the printing equipment inside the plant building were severely damaged.

Fig.17 Perfect appearance of the plant building of light-weighted structure

Fig.18 Perfect condition inside the plant building of light-weighted structure

2.1.2. Chimney of Brick Masonry

This investigation found that almost all chimneys of the enterprises suffered damage of different degrees, and most of the independent brick chimneys are severely damaged, which had circular cracks at the bottom and collapsed severely at about 1/4~1/3 on the top. For example, in the case of Sichuan Hengtai Environmental Technology Co., Ltd. affiliated to China Academy of Engineering and Physics, the nearby desulfurization facilities the brick chimney were severely damaged due to collapse of the chimney. Damage to the equipment was estimated at millions of yuan.

Fig.19 Circular cracks in the upper middle part of the chimney

Fig.20 The chimney groups almost completely broken and collapsed

2.1.3. Water Tower Structure

In the case of the water tower structure, due to heavy mass of the top, horizontal seismic shear and moment of flexure suffered at the bottom of the water tower are also high under the action of horizontal ground motion load, causing cracks at the bottom.

Fig.21 Water tower structure

Fig.22 Cracks at root of the water tower structure

2.1.4. Cement Bunker

Since the cement bunker contained a huge amount of cement raw material and clinker, the mass was very heavy, and so did the horizontal seismic force, causing a number of circular cracks or even breakages and displacements at the mid height of the bunker. The investigation found that bunkers contained no materials didn’t suffer much damage in this earthquake.

Fig.23 Circular cracks and displacements at mid height of individual cement bunker

Fig.24 Circular cracks and displacements at mid height of multiple cement bunkers

2.1.5. Foundation of Large Equipment

Many large equipment such as the imported high-precision printing equipment and textile equipment suffered damage due to tilting and slipping resulted from the earthquake. Since these large equipment were not fixed with the ground or the flooring by using anchor bolts, the equipment were tilted and damaged, and should be repaired. Downtime of the enterprises brought about huge economic loss. See Fig.25.

2.1.6. Seismic Joint

Buildings on both sides of the seismic joint suffered damage as a result of collision under the action of the earthquake. The collision even contributed to the partial collapse of the buildings. Falling objects have caused a certain damage to human beings. See Fig.26 to 27.

Fig.25 The printing equipment was shut down due to damage of buildings

Fig.26 Partial collapse resulted from collision of buildings on both sides of the seismic joint

Fig.27 Damage and falling of glass curtain walls resulted from collision of the seismic joint

2.1.7. Boilers

Due to unstable foundations, many boilers became inclined or even collapsed during the earthquake. Boilers cannot be used normally or even endanger safety of the operators.

2.1.8. Underground and Above-ground Pipelines

Since Wenchuan Earthquake is a shallow-focus earthquake, it caused severe damage to the underground and above-ground pipe grids. For example, the high-, mid- and low-pressure pipe grids of Mianyang Fuel Gas Group Corporation suffered severe damage in this earthquake. Direct economic loss associated with the pipe grids is estimated at 42.66 million yuan. Due to the damaged pipe grids, the natural gas company cannot supply gas to local enterprises, as a result, other gas consuming enterprises cannot resume their production.

2.2.Characteristics of Earthquake Damage to Industrial Buildings

Earthquake damage to industrial buildings is closely related to the year when the buildings were built. Plant buildings constructed in different periods adopted different earthquake fortification codes, as a result, earthquake fortification capabilities of the structures are different. China's earthquake fortification codes mainly involve three stages: 1979 code, 1989 code and 2001 code. Plant buildings designed before 1979 basically copied foreign codes in design, without any consideration for earthquake fortification design. These kind of buildings were severely damaged or even collapsed in this earthquake. For this part of plant buildings, we suggest that earthquake resisting reinforcement should be immediately carried out, and suggest to demolish the plant buildings which are not worthy of earthquake-resisting reinforcement; plant buildings between 1980 and 1989 were mainly designed according to 1979 code, and the earthquake fortification design was of low level, which suffered medium-degree damaged in this earthquake; plant buildings designed between 1989 and 2001 according to 1989 code tend to have an excellent earthquake resisting capacity, the principal part of which basically remained perfect or suffered slight damage in this earthquake, although non-bearing structures of some of the plant buildings of this type suffered severe damage, but can be continually used after restoration. Principal part and cladding structures of plant buildings of light-weight steel structure designed after 2001 were not damaged at all in this earthquake. The investigation found that principal parts of plant buildings designed after 2001 according to 1989 code and 2001 code are safe, meeting the earthquake fortification objectives of "no damage in minor quake, repairable after medium-level quake and no collapse in major quake", which means, in the event of an earthquake lower than the fortification intensity for this region, damage to the plant buildings should be slight, and the plant buildings can be used without any repair; in the event of an earthquake equivalent to the fortification intensity for this region, damage to the plant buildings should be of medium level, and they may be continually used after reinforcement and repair; in the event of rare earthquake in excess of the fortification intensity for this region, the structures should not collapse, and personal life and safety can be guaranteed.

3. PROCESS FOR HANDLING OF EARTHQUAKE DAMAGE TO THE INDUSTRIAL BUILDINGS

Emergency Assessment ⇒ Field Measurement ⇒ Earthquake Resistance Evaluation ⇒ Reinforcement Design ⇒ Reinforcement Constructoion

3.1. Emergency Assessment of Structure Safety

Emergency assessment of structure safety is presently the most urgent and tough tasks of enterprises for resuming production. According to Clause 17 of Decree No. 148 of the Ministry of Construction –"Provisions on Administration on Anti-seismic Facilities and Protection for Building Construction Projects", following a destructive earthquake, the construction administration department of a local people's government should organize an emergency assessment of the earthquake resisting capacity of the damaged houses and buildings, and should come up with a restoration and rebuilding plan. According to the results of field investigation of and seminar held by the Investigation Team, plant buildings requiring measurements and evaluations amount to an area of 8.48 million square meters. It is apparent that sole reliance on local measuring and technical force is insufficient, thus, we suggest to mobilize measuring forces of the entire nation with the construction commissions of other provinces and municipalities to support local construction administration departments in order to carry out a general survey of the structure safety of all plant buildings in this region.

3.2. Field Inspection of Plant Building Structures and Earthquake Resistance Evaluation

According to Clause 18 of Decree No. 148, buildings should be evaluated according to the earthquake resistance evaluation standard if required so as a result of emergency assessment. Those requiring repair or anti-seismic strengthening as a result of the evaluation should be repaired and reinforced according to relevant compulsory engineering construction standards. Buildings requiring further detection and evaluation as a result of emergency assessment of the structure safety must be checked and evaluated by institutions having proper qualifications through mobilizing technical forces of the entire nation.

3.3. Structure Strengthening Design

Since surface magnitude of Wenchuan Earthquake is Ms8.0 and the hypocenter is very shallow (only 19km from the ground surface), and the epicenter is only 150km from Mianyang City, thus, the earthquake intensity generated in Mianyang Region was generally higher than the intensity specified in the Chinese national standard “Code for Seismic Design of Buildings”. According to Clause 18 of Decree No. 149, when the actual intensity of an earthquake occurred is higher than the corresponding basic earthquake intensity specified in the Zonation Map of Earthquake Ground Motion Parameters in China, earthquake fortification design of buildings to be repaired or constructed after the earthquake should be designed in accordance with the verified results of ground motion parameters issued by the state earthquake authority. Reinforcement design of the plant building structure as well as earthquake resistance re-verification on the actual intensity of this earthquake should be carried out by institutions having the reinforcement design qualifications in accordance with the field inspection and earthquake resistance evaluation results.

3.4. Construction of Structure Reinforcement

To ensure the post-quake reinforcement construction quality of the buildings, the earthquake resistance reinforcement construction should be carried out by institutions having structure reinforcement qualifications, during which priority shall be given to the quality of the reinforcement materials and construction works.

4. SUGGESTIONS FOR POST-QUAKE REINFORCEMENT AND REPAIR

The post-quake reinforcement and restoration may adopt such mature structure reinforcement technologies currently available as pressurized chemical crack grouting, patching with polymer mortar or epoxy mortar, reinforcement with bonding carbon fiber, reinforcement with steel plate and reinforcement with steel wire mesh, etc. Their respective applications for handling of earthquake damages are briefly described below:

4.1. Pressurized Chemical Crack Grouting

Cracks in the concrete structures occurred during the earthquake are patched by pressurized grouting. The pressurized grouting is applied for cracks with a width greater than 0.1mm in beams, slabs and columns by using grouting material. When the grouting material is injected in the cracks inside the structures, the cracks can be blocked, and strength, durability and integrity of the concrete structures are thus restored and improved. See Fig.28

4.2. Patching with Polymer Mortar or Epoxy Mortar

To patch the peeled off protection layer of the concrete as well as exposed rebars of the concrete structure occurred in the earthquake, polymer mortar or epoxy mortar can be used to patch the defect layer by layer until it reaches the cross-section dimensions of the original structure. In addition, interfacing agent is applied at the joint faces between the old and new structures so as to increase the cementing strength between the new and old concrete.

Fig.28 Pressurized grouting into cracks

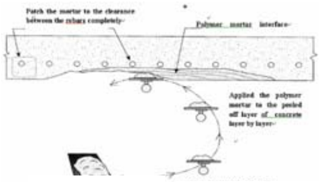

Fig.29 Patching with polymer mortar

4.3.Reinforcement with Bonding Carbon Fiber

Insufficient bearing capacity of the beam, slab and column of concrete structure can be reinforced by pasting carbon fiber fabric. This kind of fabric can improve earthquake resistance and elongation of concrete columns especially when it is used to wrap the columns laterally, which is characterized by fast speed, high efficiency and easy construction.

Fig.30 Reinforcement by wrapping carbon fiber sheet around the column

Fig.31 Reinforcement of beam and slab by pasting carbon fiber sheet

4.4. Reinforcement by Pasting or Wrapping Steel Plate

For reinforcement of beams, steel plate of a certain thickness is usually pasted on the bottom of the beam to improve its bending resistance and bearing capacity, and U-shaped steel collar is pasted on the side of the beam to improve its shear strength and bearing capacity. For reinforcement of columns, angle steel or steel plate is usually wrapped on their outside.

Fig.33 Reinforcement of column by wrapping steel plate

Fig.34 Reinforcement by pasting steel plates on the bottom and sides of the beam

Fig.35 Steel plate is fixed by using chemical anchoring bolts

4.5. Reinforcement with Steel Cable Mesh Pad

High-strength stainless steel wire mesh is placed on the beam bottom, beam side or laterally on the column, which is then fixed with the concrete by using pins. And then polymer mortar is sprayed on the mesh to further strengthen the concrete elements and improve the earthquake resistance of the beams and columns.

Fig.35 Steel wire mesh placed on bottom of the beam

Fig.36 U-shaped steel wire mesh placed on side of the beam

4.6. Reinforcement by Increasing Cross-section

The increase of cross-section by using concrete is a traditional structure reinforcement method, and is also an effective reinforcement method for improving earthquake resistance of structures. Demonstrated in the following pictures is the construction procedure for cross-section increase.

Fig.37 Roughening of the surface of the original concrete column

Fig.38 Longitudinal rebars of the column threading through the floor slab

Fig.39 Column with cross-section increased

4.7. Reinforcement with Shotcrete

In order to dramatically improve the overall earthquake resistance of brick masonry structures, mat reinforcement is usually suspended on the inside and outside of the masonry, on which shotcrete is then applied to form a concrete sandwich wall. Under pressure, shotcrete can be bonded with the masonry excellently to form an integral structure to jointly resist horizontal earthquake load and vertical load. There have been many successful examples in high earthquake intensity regions such as Beijing adopting this method to improve the earthquake resistance of masonry structures without ring-beam and structural column. The following pictures Fig.40 shows the reinforcement of a hotel building in Beijing.

4.8. Improving Horizontal Earthquake Resistance by Adding Steel Supports or Concrete Shear Walls

For frame structures having poor horizontal earthquake resistance, depending on the plane arrangement of the structure and under the precondition of non-interference with the functions of the building, the building's capability to resist horizontal earthquake load can be dramatically improved by adding steel supports or concrete shear walls in proper positions. However, the frameworks connected with the shear walls or steel supports should generally be reinforced too. See Fig.41,the added shear wall is under construction.

4.9. Adding Damper for Earthquake Resisting Reinforcement

This is not the traditional method for improving overall lateral rigidity of a building, but involves the adding of an energy consuming structure (such as a damper) capable of absorbing the earthquake energy in a proper position of the plane of the structure in an effort to reduce the horizontal earthquake action on the structure. See Fig.42.

4.10. Shock Isolation and Absorption Technologies

Damper or rubber bearing is generally placed at the foundation of a building or equipment to absorb the earthquake energy and prevent a large amount of earthquake energy from being transferred to the upper structure for the purpose of shock isolation and absorption. In this manner, the upper structure is protected from damage by the earthquake. See Fig.43

Fig.40 reinforcement of the masonry of a hotel building in Beijing with shotcrete

Fig.41 the added RC shear wall

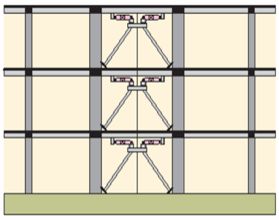

Fig.42 Adding damper for reinforcement

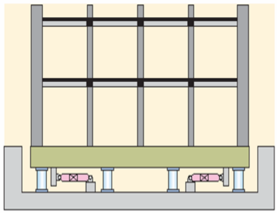

Fig.43 Shock isolation and absorption of foundation

5. SUGGESTIONS FOR EARTHQUAKE FORTIFICATION DESIGN OF INDUSTRIAL PLANT BUILDING IN THE FUTURE

Field investigation indicates that the 5.12 Wenchuan Earthquake has caused devastating damage to industrial buildings of Mianyang City built in Qinglongshan Fault Zone, such as Beichuan County, Nanba Town of Pingwu County as well as Jiangyou City, etc. Industrial buildings in the entire Beichuan County and Nanba Town of Pingwu County were almost leveled to the ground. This earthquake gave a profound lesson for seismic design of industrial buildings, to which priority must be given during seismic design of plant buildings in the future.

5.1. Attention Shall be Given to Site Selection for Industrial Buildings.

Site of important industrial enterprises should avoid fault zones with active earthquake. Attention shall be given to earthquake safety assessment of the site, and plant buildings should not be built on sites with high risk of earthquake and liquefaction. The investigation found that secondary disasters such as mountain slide, etc. caused by the earthquake had caused the entire plant buildings to be buried in some cases, causing major personal injuries and deaths as well as major economic loss of the enterprises. Secondary disasters associated with earthquake are also one of the important factors which shall be taken into account when selecting sites for the plant buildings.

5.2. Attention Should be Given to Earthquake Resistance, Shock Absorption and Isolation of the Foundations of Large-scale Industrial Equipment and Precision Equipment.

Precision equipment, especially electronic equipment should have the function for automatic detection of ground motion, which can take safety protection measures such as Auto Stop or Auto Locking, etc. once any ground motion endangering safe operation of the equipment is detected. The application of shock isolation and absorption technologies, such as comprehensive earthquake resistance and shock absorption measures like the provision of shock-isolating rubber pads, dampers, etc., is encouraged in regions of high intensity, or in very important plant buildings, especially in foundations of very important plant buildings or precision equipment, in order to improve the overall earthquake resistance level of the plant building structures.

5.3. Attention Should be Given to Types of Industrial Plant Building Structures

The type of structure with an excellent earthquake resistance must be selected. This investigation indicates that almost all plant buildings of light-weighted steel structure (most of them are gantry type steel framework) have withstood the testing of this earthquake, whose principal structures and exterior cladding structures suffered no damage in the earthquake. We suggest that plant buildings of this light-weighted steel structure be vigorously promoted, and scientific research on the earthquake resistance of this type of plant building structure be strengthened, for example, the diaphragm effect of the exterior enclosure of light-weighted steel structure favorable for earthquake resistance of the structure, etc., so that code, standard as well as relevant drawing register suitable for this region can be developed.

5.4.Attention Should be Given to Seismic Design of the Chimney Structure and Boiler Foundation

This investigation also found that more than 90% of the brick chimneys suffered circular cracks, displacement, partial collapse or total collapse, which require reinforcing repair, partial demolishment or total rebuilding, causing the enterprises to stop their production, resulting in a huge economic loss. It is suggested that high-rise chimneys to be built in this region in the future should adopt RC structure with good earthquake resisting performance. Height of brick chimneys should be strictly limited, and necessary distance must be kept.

This earthquake also caused boilers of many companies to become inclined, and the boilers currently cannot be used normally, requiring correction or demolishment. We suggest that priority be given to seismic design of the boiler foundations so as to prevent the horizontal action of the earthquake from resulting in inclination or collapse of the boiler.

5.5. The use of masonry plant buildings without concrete ring-beams and structural columns should be strictly limited in the high earthquake intensity regions and plant buildings of light-weighted steel structure should be vigorously promoted.

5.6. It is encouraged that large-scale or important plant buildings be designed according to performance-based design methods, and different earthquake resistance targets should be defined according to different requirements of the owners, based on which seismic design of structures should be carried out.

5.7. To push forward smooth repair and reinforcement of the plant buildings damaged, we suggest that the state's earthquake authority could speed up its collection, analysis, study of the observed ground motion data of Wenchuan Earthquake as well as its investigation of the earthquake damage, and issue, at the earliest, the intensity distribution map of this earthquake, the ground motion parameters for seismic design of building structure as well as the design reaction spectrum.

5.8. It is our suggestion that attention should be given to overall collapse of buildings caused by damage of individual structural element due to earthquake as far as structure of the plant buildings is concerned. Effective measures must be taken to prevent progressive collapse of the structures. We suggest to prohibit use of plant building structure made of precast slabs in regions such as this city where the earthquake intensity is high. Instead, integrally-cast RC floor slabs should be used to improve integrity and earthquake resistance of the structures.

5.9. Attention should be given to seismic design of underground and above-ground pipe grids, especially the ones that could bring about danger, toxic gas, liquid leak and danger to personal safety when broken.

5.10. Since stairs are the important escape passages during earthquake, we must pay close attention to the seismic design of the staircases of the plant buildings. Since horizontal rigidity of the staircase is weakened to a large extent due to existence of the opening, horizontal breakage of the stair flight as a part of the earthquake damages indicates that horizontal rigidity of this part should be strengthened, possibly through strengthening rigidity of the beam posts around the stair opening. Connection between the partition wall of the staircase and the beam posts must also be strengthened structurally so as to prevent the collapse of the partition wall during an earthquake from blocking the escape passage.

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