Seismic Hazard Assessment for Chlorine Building

Building Description

The indicative layout plan of the chlorine store is as shown in Figure 1. Considering the dimensions of the chlorine store for the desalination plant, the chlorine store for Au Tau WTW is used as a reference design. Parameters of the chlorine store are summarized in Table 1.

The chlorine store occupies floor area 28m x 20m of the chlorine building which is located in the middle of the desalination plant with area of 46m x 20m. Apart from chlorine store, the chlorine building provides compartments for evaporators, chlorinators, chlorine scrubber and control room as well as electrical and mechanical facilities. The chlorine building is a single story reinforced concrete frame structure with unreinforced infill masonry walls around the perimeter of the building. There are a number of internal walls with full height of the building to form compartments for other chlorine facilities. The vertical load carrying structure consists of concrete roof slab, supported on secondary beams, spanning deep concrete beams that provide a 20m wide column free space in the chlorine store.

There are 2 overhead cranes in the chlorine store. Each overhead crane spans half width of the chlorine store and runs along the length of the chlorine store. They are suspended from beams fixed to the roof structure. The chlorine scrubber is an integral part of the chlorine building. There is no adjacent building with adjoining side wall. Moreover, adjacent buildings have similar elevation and the distance between adjacent buildings is at least 3m. Therefore, no adjacent building poses a seismic hazard.

Since the chlorine building is constructed of reinforced concrete, it will either fail catastrophically or not at all in earthquakes. Therefore, there is no partial failure mode of the chlorine building.

The chlorine building is classified as Group 1 building by following the evaluation method as adopted in Arup (2001). The evaluation is based on the methodology developed by the Federal Emergency Management Agency (FEMA) using checklists in the screening phase (Tier 1) and analyses in the evaluation phase (Tier 2) of FEMA 310 (1998). Evaluation results are summarized in Table 3 and compared with 8 existing chlorine buildings. The evaluation results are supplemented with the details of FEMA screening phase checklist (Tier 1) and evaluation phase analysis (Tier 2) as presented in Table 4 and Table 5 respectively.

Minor Consequences

Referring to Vision 2000 (1995) and Arup (2001), minor consequences include minor building damage and moving containers.

Minor Building Damage

Minor building damage would lead to moderate to severe damage to architectural systems and dislodged / overturned mechanical, electrical and plumbing (MEP) systems such as significant falling of lights fittings and ducts but little structural damage. Due to the relatively light in weight, the impact energy of falling light fittings and ducts would be quite low and present no risk of splitting the chlorine containers. It is possible that an exposed valve and piping between chlorine containers and chlorinator may be damaged in a direct hit by the corner of a falling fitting or duct. However, the risk of chlorine release is low.

Moving Containers

The movement of an on-duty chlorine drum may lead to the connecting piping failure because of the excessive strain beyond the design tolerance limit. According to the response spectra as shown in Figure 4.4 of Arup (2001), the displacement leading to such high strain situation requires the peak ground acceleration in the order of 2g. Under this level of peak ground acceleration, major consequences such as structural damage to the chlorine building and roof collapse would occur. Therefore, minor consequence caused by drum movement is not separately considered.

Moderate Consequences

Infill Wall Failure

Referring to Arup (2001), unreinforced brick masonry walls between the main structure comprising reinforced concrete frames were assumed in calculations. The calculations show that there will be insufficient concentrated energy from the falling brickwork to split a chlorine drum. Considering the height of the chlorine building and the distance between brick walls and chlorine drums, it would be appropriate to adopt the calculation findings to the desalination plant.

Crane Collapse

Total number of 2 overhead cranes would be installed for the transfer of chlorine drums within the chlorine store. The span of each overhead crane is approximately 10m. The cranes are parked at the loading bay away from the storage area to avoid potential damage to chlorine drums by a dislodged crane when they are not in use. Referring to the reassessment study for Sheung Shui WTW, the weight of a 10m overhead crane is about 10kN. The impact energy of a falling crane is 65kJ and is much smaller than the threshold energy for damaging a chlorine drum (133kJ). Therefore, the crane collapse event is not further considered in the QRA.

Major Consequences (Roof Collapse)

While the depth of main beams is greater than the depth of secondary beams, main beams would hit chlorine drums underneath the collapsed roof prior to secondary beams. Chlorine drums would vastly absorb the impact energy of the roof from main beams. Therefore, it is anticipated that secondary beam would not affect chlorine drums in the store.

Because of vibration in an earthquake, the roof may not fall in the strictly vertical direction and land on the ground at the same position on the horizontal plane as the original. Although chlorine drums may be arranged to avoid directly underneath of main beams, they may still be hit by main beams because of the horizontal shift. The magnitude of the shift depends on the height of the roof. When the number of affected drums is estimated, the roof is allowed to shift along X and Y directions with total 8 combinations (+X, -X, +Y, -Y, +X+Y, +X-Y, -X-Y, -X+Y) for the distance equal to the height of the roof to account for the dislocation of the collapsed roof.

Main beams are 300mm in width. Considering sufficient separation between 2 consecutive drums in a row, a main beam would not hit 2 adjacent drums at the same time. Having considered the layout of main beams and chlorine drums as well as the shift of roof position, it is estimated that 4 drums, 5 drums and 8 drums would be affected with probability of 25%, 37.5% and 37.5% respectively by referring to Table 2. Therefore, the average number of affected drums is estimated as 6.

Depending on the position of an impact, the chlorine drum would suffer from the worst damage when it is directly hit by the collapsed roof right on the top. On the other hand, chlorine drums being hit at their sides may not lead to rupture. Therefore, the number of ruptured drums should also consider the probability of rupture in an impact as follows,

Number of ruptured drums = (Number of affected drums) X (Probability of drum rupture in impact)

By adopting a conservative approach, it is assumed the probability of drum rupture in impact is equal to 1.

In a roof collapse event, part of the chlorine discharged from ruptured drums would be trapped by debris of the chlorine store. After the instantaneous discharge of chlorine from ruptured drums, it is estimated that 70% of the chlorine is released to atmosphere as vapour and entrained aerosol. The chlorine vapour cloud is contributed by the initial vapour flash fraction (19%), the entrained aerosol (2 x 19%) and evaporating chlorine pool over the first minute (10% depending on the chlorine pool size). Referring to the Reassessment Study for 8 WTWs, 7% and 10% were taken for the contribution of evaporating chlorine pool. Adopting a conservation approach, a larger value is used in this assessment.

Table 1 Typical Layout of the Chlorine Store

Chlorine store	Unit	Desalination plant (RC roof)	Au Tau WTW
Store Parameters			
Plan dimension (length)	m	28	30
Plan dimension (width)	m	20	15
Roof height	m	7.5	6.5
Typical main beam			
Size – width x depth	mm	300 x 1200	300 x 1200
Span	m	20	15
Spacing	m	9.35	10
Typical secondary beam			
Size – width x depth	mm	300 x 500	300 x 500
Span	m	9.35	10
Spacing	m	3.35	3.75
Roof area	m^2	560	450
Roof slab weight per unit area	kN/m^2	10.7	5.3
Total roof weight	kN	5988.0	2400
Roof height above container	m	6.5	5.2
Total number of containers	drums	37	66
Calculated Impact Energy			
Total impact energy of the collapsed roof	kJ	38922	12480
Average impact energy on each drum	kJ/drum	1052	189

Table 2 Number of Drums Affected

Direction of Shift	+X	-X	+Y	-Y	+X+Y	+X-Y	-X-Y	-X+Y
Number of drums affected	8	5	4	4	8	8	5	5

Modeling of Seismic Hazards in the QRA

Earthquake Frequency

The assessment of seismic hazards in the QRA for Desalination Plant focuses on earthquakes which could cause roof collapse leading to multiple catastrophic failure of chlorine drums. Two magnitudes of earthquake are considered, 0.7g/MMXI (10% chance of roof collapse) and 1.0g/MMXII (50% chance of roof collapse) as shown in Figure 2 (Figure 8.1 in Arup (2001)) for chlorine buildings under Group 1 category.

Surrounding Population

When an earthquake leads to collapse of chlorine building and release of chlorine, it is expected that surrounding buildings are also devastated. People in those buildings would be killed by the collapsed buildings rather than chlorine. Therefore, people surviving from the earthquake are only considered in the QRA. Depending on the magnitude of the earthquake, event trees as shown Figure 3 are used to derive surviving percentage of indoor population for the 2 ground peak acceleration levels.

References

Ove Arup & Partners (2001), Water Treatment Works Seismic Hazard Assessment, Seismic Assessment of Chlorine Storage Buildings and Chlorine Containers, WSD.

Vision 2000 Committee (1995), Performance Based Seismic Engineering of Buildings, Structural Engineers Association of California, April 1995.

Cook, I., N. J. Holloway, W. Nixon and D.W. Phillips (1993), Consultancy on the Environmental Aspects of the Daya Bay Nuclear Power Station for the Government of Hong Kong - Risk Assessment Report.

Federal Emergency Management Agency (1998), FEMA 310, Handbook for the Seismic Evaluation of Buildings--A Prestandard.

Table 3 Summary of Analysis of FEMA Evaluation Statements and Grouping

Building Group	Site Name	Date of Construction	Number of Stories	General Building Condition [1]	FEMA Evaluation Statements [2][3]							Site Response Factor	Structural Performance Rank X/Y [4]
					Adjacent Structures	Vertical Discontinuity	Torsion	Redund-ancy	Shear Stress Check URM/CSW	Proport-ions	Infill Walls		
1	Desalination plant	New construction	1	Very Good	C	NC	C	C	C	NC	NC	2.0	A
	Sha Tin	1993	1	Good	C	NC	C	C	C	NC	NC	1.0	A
	Au Tau	1992	1	Good	NC	NC	C	C	C	NC	NC	2.0	A
	Pak Kong	1992	2	Good	NC	NC	C	C	C	NA	NA	1.8	A
2	Sheung Shui	1980's	1	Fair	NC	C	C	C	C	NC	C	1.0	A
	Yau Kom Tau	1985	1	Good	NC	C	C	C	NC	NC	C	1.5	C/C
	Tuen Mun	1978/1994	1	Fair	NC	NC	NC	NC	NC	NC	NC	1.0	B/C, A/D
	Tsuen Wan	1970's	1	Good	NC	NC	NC	NC	NC	NC	NC	1.8	C/D, E/D
3	Tai Po Tau	1968	1	Good	NC	NC	NC	NC	NC	NC	NC	1.3	E/D

Notes:

1. Building condition scale: very poor, poor, fair, good, very good,
2. For details of the FEMA evaluation statements refer to Table 4.
3. FEMA evaluation statements: C – compliant; NC – non-compliant.
4. Structural performance rank see Table 5.

Table 4 FEMA – Tier 1 Seismic Evaluation of the Chlorine Building for Desalination Plant

		Site Name	Pak Kong	Au Tau	Sha Tin	Desalination Plant	
Key building data		Chlorine store part of existing building	Yes	Yes	Total building	Total building	Standalone chlorine building
		Date of construction	1992	1992	1993	New construction	
		Number of stories	2	1	1	1	
		Building height	13.1	6.5	8	7.5	
		Story height	5	6.5	8	7.5	
		Expansion joint in building	Yes	Yes	No	No	
		Adjacent structure	Yes	Yes	No	No	
		Type of crane	Hung	Hung	Rail	Rail	
		General building condition	Good	Good	Good	Very good	New construction
		Number of chlorine containers	60 drums	150 drums	203 drums	37 drums	
		Number of chlorine containers in use	5	5	5	4	
		Region of seismicity	Low/ moderate	Low/ moderate	Low/ moderate	Low/ moderate	
		FEMA Type X direction	Type 9 C2	Type 9 C3	Type 9 C3	Type 10 C3	Infill masonry walls with reinforced concrete frame
		FEMA Type Y direction	Type 9 C2	Type 9 C3	Type 9 C3	Type 10 C3	
		Performance level	LS	LS	LS	LS	
Basic structural checklist	Building system	Load path	C	C	C	C	
		Adjacent buildings	NC	NC	C	C	No adjoining or adjacent building
		Mezzanines	NA	NA	NA	NA	
		Weak story	NA	NA	NA	NA	
		Soft story	NA	NA	NA	NA	
		Geometry	NA	NA	NA	NA	
		Vertical discontinuities	NC	NC	NC	NC	Window / door openings
		Mass	C	NA	NA	NA	1 story only
		Torsion	C	C	C	C	[3]
		Deterioration of concrete	C	C	C	C	New construction with proper maintenance

		Site Name	Pak Kong	Au Tau	Sha Tin	Desalination Plant	
		Masonry units	NA	C	C	C	New construction
		Masonry Joints	NA	U	U	C	New construction
		Cracks in infill walls	NA	NC	C	C	New construction
		Cracks in boundary columns	C	C	C	C	New construction
	Lateral force resisting system	Redundancy	C	C	C	C	
		Shear stress check RM	NA	NA	NA	NA	
		Shear stress check URM/CSW	U	U	U	U	Refer to calculations in Table 5
		Wall connections	C	U	U	C	All infill walls shall have a positive connection to the frame to resist out-of-plane forces
Supplemental structural checklist	Lateral force resisting system	Deflection compatibility	U	U	U	U	
		Flat slabs	NA	NA	NA	NA	
		Reinforcing at openings	NA	NA	NA	NA	
		Proportions	NA	NC	NC	NC	Height to thickness ratio of shear wall >30
		Solid walls	NA	C	C	C	
		Infill walls	NA	NC	NC	NC	Not continuous to the soffits of the frame beam
Basic structural checklist	Connections	Transfer to shear walls	C	U	U	U	
		Concrete columns	C	U	U	U	
		Lateral load at pile caps	NA	NA	NA	NA	
Supplemental structural checklist	Diaphragms	Diaphragm continuity	C	C	C	C	Not composed of split-level floors
		Openings at shear walls	C	NA	C	C	Openings immediately adjacent to the shear walls <25% of wall length
		Plan irregularities	NA	NA	C	NA	
		Diaphragm reinforcement at openings	NC	U	NA	NA	
Geological site hazard & foundation	Geological site hazards	Liquefaction	C	NC	C	C	
		Slope failure	C	C	C	C	
		Surface fault rupture	C	C	C	C	

		Site Name	Pak Kong	Au Tau	Sha Tin	Desalination Plant	
checklist	Condition of foundations	Foundation performance	C	C	C	C	
		Deterioration	C	C	C	C	
	Capacity of foundations	Overturning	C	C	C	C	
		Ties between foundation elements	C	U	U	C	
		Deep foundations	C	U	U	NA	
		Sloping sites	NC	NA	NA	NA	
Basic non-structural checklist	Partitions	Unreinforced masonry	NA	NC	NA	NC	
	Ceiling systems	4 statements	NA	NA	NA	NA	
	Light fixtures	Independent support	NA	NA	NA	NA	
		Emergency lighting	C	C	C	C	
	Cladding & glazing	9 statements	NA	NA	NA	NA	
	Masonry veneer	3 statements	NA	NA	NA	NA	
	Parapets/ appendages	URM parapets	NA	U	U	U	
		Canopies	U	U	U	U	
	Masonry chimneys	2 statements	NA	NA	NA	NA	
	Stairs	URM walls	NA	NA	NC	NA	
		Stair details	NA	NA	NA	NA	
	Building contents	1 statement	NA	NA	NA	NA	
	M&E equipment	Emergency power	U	U	U	U	
		Heavy equipment	NC	NC	NC	NC	
	Piping	Fire suppression piping	NA	NA	NA	NA	
		Flexible couplings	NC	NC	NC	NC	
	Hazardous materials	Toxic substances	C	C	C	C	
Supplemental non-structural checklist	Partitions	Drift	NA	U	NA	U	
		Structural separations	NA	C	NA	C	No partition at structural separation; otherwise shall have control joints
		Tops	NA	NA	NA	NA	
	Ceiling systems	Edges	NA	NA	NA	NA	
		Seismic joint	NA	NA	NA	NA	

		Site Name	Pak Kong	Au Tau	Sha Tin	Desalination Plant	
	Light fixtures	Pendant supports	C	C	C	C	[4]
		Lens covers	U	U	U	U	
	Masonry veneer	5 statements	NA	NA	NA	NA	
	Metal stud back up systems	2 statements	NA	NA	NA	NA	
	Concrete block & masonry backup systems	3 statements	NA	NA	NA	NA	
	Parapets	Concrete parapets	C	U	U	U	
		Appendages	C	U	U	U	
	Building contents	4 statements	NA	NA	NA	NA	
	M&E equipment	Heavy equipment	NC	NC	NC	NC	
		Vibration isolators	NA	NA	NA	NA	
		Electrical equipment	NA	NA	NA	NA	
	Piping	Fluid & gas piping	U	U	U	U	
		Shut-off valves	U	U	U	U	
		C clamps	U	U	U	U	
	Ducts	Duct bracing	NA	NA	NA	NA	
		Stairs & smoke ducts	NA	NA	NA	NA	
		Duct support	C	C	NA	NA	
	Hazardous materials	Gas cylinders	NA	NA	NA	NA	
		Hazardous materials	C	C	C	C	Piping shall have shut-off valves
	Elevators	8 statements	NA	NA	NA	NA	

Notes:

1. Evaluation of statements in FEMA 310 is as follows, C = Compliant – no further investigation required; NC = Non-compliant – Tier 2 investigation required; NA = not applicable; U = Unknown – Tier 2 investigation required.
2. Details description of the Evaluation Statements and examples of the evaluation sheets refers to Appendix D of Arup (2001) and FEMA 310 (1998).
3. The distance between the story centre of mass and the story centre of rigidity shall be less 20% of the building width in either plan dimension.
4. Light fixtures on pendant supports shall be attached at a spacing of equal to or less than 6 ft and, if rigidly supported, shall be free to move without damaging adjoining materials.

Table 5 Structural Performance Rank

Site Name	Pak Kong	Au Tau	Sha Tin	Desalination plant	Reference
Modification factor, C	1.2	1.4	1.4	1.4	for shear wall, 1 story
Site response factor, S	1.8	2	1	2	make reference to Au Tau for the worst loading in calculation; also refer to Table 3-5 in FEMA 310 corresponding to Site class D for the soil properties at TKO 137 and S1=0.2.
Peak ground acceleration	0.2	0.2	0.2	0.2	
Response spectral acceleration	0.9	1	0.5	1	make reference to Au Tau; Also, T=0.22s and S_{D1}=0.2 are calculated according to Equation (3-7) and Equation (3-5) in FEMA 310 [5] respectively. Spectral acceleration is estimated as ~1 (=S_{D1}/T) according to Equation (3-4) in FEMA 310 [5].
m factor for walls	4	1.5	1.5	1.5	for unreinforced masonry wall
m factor for columns	2	2	2	2	for buildings being evaluated to the Life Safety Performance Level
Dimension, X (m)	40	22.5	22	46	
Dimension, Y (m)	34	40	54	20	
Floor area (sq.m)	1360	900	1188	920	Calculated
Weight, W (kN/sq.m)	19.3	5.3	13.2	10.7	
Story weight, DL+LL (kN)	26248	4770	15682	9844	Calculated
Story shear, V (=CSW) (kN)	28348	6678	10977	13782	Calculated
Wall shear check					
Estimated wall thickness (mm)	200	225	225	225	
Length of wall, X (m)	-	67.5	38	84	
Length of wall, Y (m)	-	110	84	60	
Area of wall, X (sq.m)	29.1	15.2	8.6	18.9	

Site Name	Pak Kong	Au Tau	Sha Tin	Desalination plant	Reference
Area of wall, Y (sq.m)	18.4	24.8	18.9	13.5	
Shear stress in walls, X (N/sq.mm)	0.24	0.29	0.86	0.49	Calculated
Shear stress in walls, Y (N/sq.mm)	0.39	0.18	0.39	0.68	Calculated
Allowable shear stress (N/sq.mm)	1.5	0.14	0.14	0.14	make reference to Au Tau and Sha Tin for requirements on specifications.
C/D ratio, X direction	6.2	-	-	-	
C/D ratio, Y direction	3.9	-	-	-	
Performance rating. X direction	A	-	-	-	
Performance rating. Y direction	A	-	-	-	
Comments	Discontinuous walls not included	Not relevant due to short columns	Not relevant due to short columns	Not relevant due to short columns	
Column shear check					
Number of columns	25	19	20	16	refer to chlorine building layout
Column size, X (m)	-	0.5	1.5	0.8	to achieve C/D ratio > 1
Column size, Y (m)	-	0.5	1.2	0.8	to achieve C/D ratio > 1
Total area of columns (sq.m)	11.7	4.75	36	10.24	Calculated
Shear stress in column (N/sq.mm)	1.21	0.70	0.15	0.67	Calculated
Allowable shear stress (N/sq.mm)	1.5	1.5	1	1.5	make reference to Au Tau for requirements on specifications
C/D ratio	1.2	2.1	6.6	2.2	Calculated
Performance rating	A	A	A	A	
Comments	-	-	-	-	

Notes:

1. For the directions see chlorine store plan in Figure 1.
2. Masonry has been assumed to be in fair condition and in accordance with default values in FEMA273, referring to Arup (2001).
3. Concrete shear stress values assumed from Aoyama (1981) related to h/d ratio, referring to Arup (2001).
4. The following table gives an indication of the Performance Ratings

Performance Rating	Expected Building Performance	Approximate Capacity/Demand Ratio
A	Good	> 1.0
B	Probably behave well	0.75 – 1.0
C	May perform poorly	0.5 – 0.75
D	Is expected to perform poorly	0.25 – 0.5
E	Is expected to perform very poorly	0 – 0.25

5. FEMA 310 - Federal Emergency Management Agency (FEMA), Handbook for the Seismic Evaluation of Buildings, FEMA-310, 1998

Figure 1 **Typical Layout of the Chlorine Store**

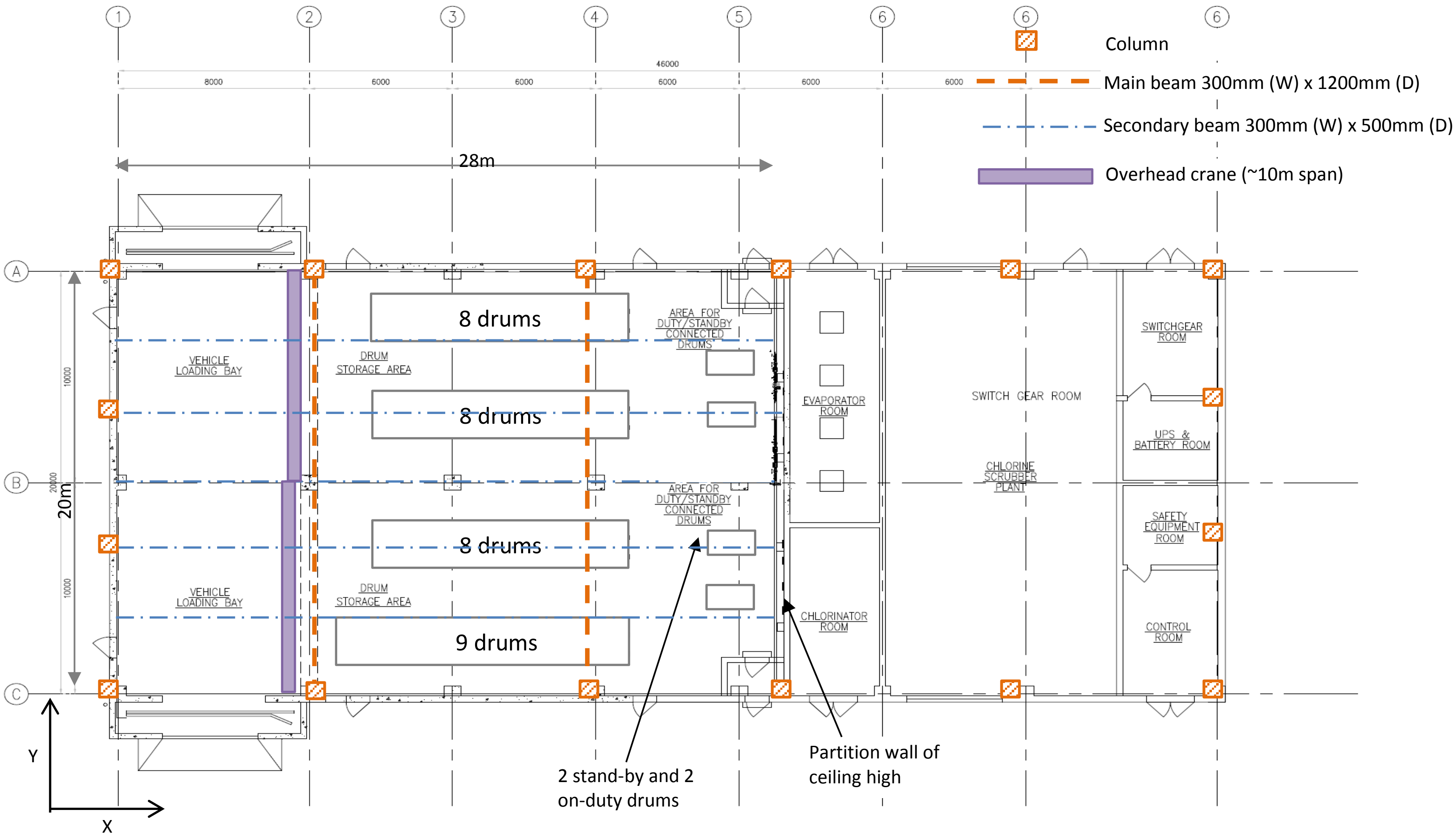

Figure 2 **Building Seismic Vulnerability Functions**

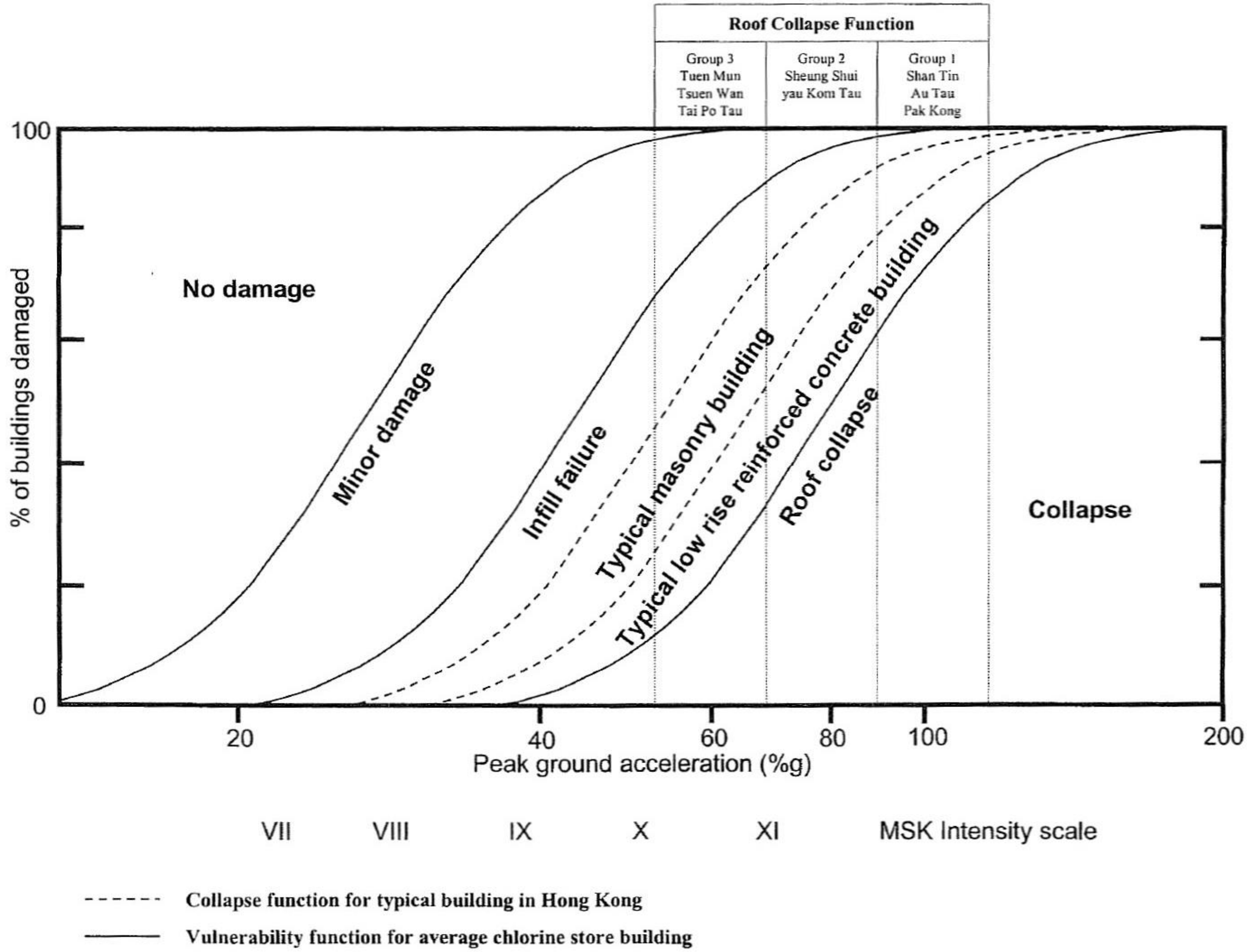

Figure 3 Event Trees for Seismic Hazards

				Outcome					
				Chlorine store	Surrounding buildings				
Earthquake magnitude	Frequency of occurrence [1] (per year)	Probability of roof collapse [2]	Event Outcome Frequency (per year)	Average number of ruptured drums [3]	Percentrage damaged	(Level of damage)	Probability of fatality [5]	Averaged probability of fatality	Surviving percentage [6]
0.7g	4.00E-07	yes 0.1	4.00E-08	6	60%	(collapse)	0.95	0.77	23%
					40%	(partial damage)	0.5		
		No 0.9	3.60E-07	0					
1.0g	2.50E-08	yes 0.5	1.25E-08	6	90%	(collapse)	0.95	0.905	10%
					10%	(partial damage)	0.5		
		No 0.5	1.25E-08	0					

Notes:
[1] from Daya Bay Risk Assessment (Cook, et al, 1993)
[2] probabilities of roof collapse from Arup (2001)
[3] number of ruptured drums estimated in this assessment
[4] refer to Figure 8.1 in Arup (2001) for typical low rise reinforced concrete buildings (ie up to 10 storeys) which represent buildings in TKO Area 137.
[5] probability of fatality for total collapse of a building estimated to be 95% and for partial damage 50%
[6] surviving % = 1 - [% collapse x P(fatality due to collapse) + % partial damage x P(fatality due to partial damage)]