

Analysis of natural and man-made accidents happened in subway stations and trains: based on statistics of accident cases

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Abstract. Sometimes subway stations and trains can be very crowded for large passenger flows. However, some stations and trains may be vulnerable when natural or man-made disasters happen, thus the safety of passengers and stuff is threatened. Therefore, it is meaningful to make a deep analysis to these disasters that may happen in subway stations and trains. By collecting cases of accidents include fire disaster, terrorist attack, flood, earthquake and stampede that happened in subway stations or on trains around the world, the causes, consequence and their own characters were analysed. Besides, some recommendations and beneficial measures aim to prevent these disasters mentioned above were also presented and discussed.

1 Background

In recent years, subway has become the first choice for many cities to solve traffic problems for its advantages of high efficiency, large capacity, low pollution and punctual arrivals. However, the large number of passengers make some subway stations and subway trains become “crowded places”, especially in peak hours. For example, the real transportation capacity of some lines and some stations in China have exceeded the designed transportation capacity during morning and evening peak hours [1, 2].

However, when emergency or disasters happen in “crowded places”, the results can be serious. Most subway stations are located underground, natural disasters such as flood and earthquake may cause serious influence to them. Besides, man-made disasters such as fire, terrorism attack can also result in devastating consequence. Worse while, most subway stations are confined spaces with just a few exit channel to the outside, the distance from platforms and tunnels to safe places can be very long, the long distance may make rescue work and evacuation harder. So it’s helpful to know the characteristics of each kind of disaster the subway station may face. In this paper, natural and man-made accidents cases include fire disaster, terrorist attack, flood, earthquake and stampede which happened in the

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subway stations and trains around the world are collected. These accidents are analyzed, and some measures aim to prevent these disasters are presented and discussed.

2 Static and analysis of subway accidents

2.1 Fire

Most subway stations are relatively confined underground spaces. If fire happens in such places, the smoke caused by the burning of synthetic materials can be toxic and also make it difficult for passengers to find escape routes, thus may results in serious injury [3]. King's Cross Station fire in London happened in 1987 and Daegu Subway fire happened in 2004 both caused more than 100 deaths or injuries [4, 5]. By literature review and news gathering, 42 subway fire cases around the world are collected and listed in table 1 [6, 7].

Table 1. Subway fire disasters around the world.

Date	City	Cause	Deaths	Injuries
1969.11.11	Beijing	electric locomotive failure	6	200
1973.03.27	Paris	arson	2	0
1974.01	Montréal	short circuit	0	0
1975.07	Boston	lighting line failure in tunnel	0	0
1976.05	Lisbon	locomotive failure	0	0
1976.10	Toronto	arson	0	0
1978.10	Cologne	cigarette butts	0	8
1979.01	San Francisco	short circuit	1	56
1979.03	Paris	short circuit of car	0	26
1979.09.	Philadelphia	transformer failure	0	178
1979.09	New York	cigarette butts	0	4
1980.04	Hamburg	seat catch fire	0	4
1980.06	London	cigarette butts	1	0
1981.06	Moscow	circuit failure	7	0
1981.09	Bonn	staff operation mistake	0	0
1982.03	New York	transmission equipment failure	0	86
1982.06	New York	arson	0	0
1982.08	London	short circuit	0	15
1983.08	Nagoya	rectifier failure	3	3
1983.09	Munich	circuit failure	0	7
1984.09	Hamburg	seat catch fire	0	1
1984.11	London	warehouse catch fire	0	18
1985.04.12	Paris	garbage on fire	0	6
1985.09	Tokyo	locomotive bearing failure	0	0
1987.11.18	London	technical failure	32	over 100
1991.04.16	Zurich	short circuit of subway locomotive	0	58
1991.06	Berlin	arson	0	18
1994.06	Taipei	substation catch fire	0	3
1995.10.28	Baku	caused by electrical malfunction	289	270
1995.04.28	Daegu	gas pipeline leakage	103	230
2001.08.30	Sao Paulo	unknown	1	27
2003.02.18	Daegu	arson in the subway train	192	148
2003.12.30	Shanghai	the fire of neighboring mall	0	0
2004.01.05	Hong Kong	arson in the car	0	14
2005.08.26	Beijing	unknown	0	0
2006.08.16	New York	unknown	0	15

2012.03.14	Kiev	chandelier line catch fire	0	0
2013.06.05	Moscow	short circuit	0	52
2014.01.05	Nanjing	flammable material brought by passenger	0	0
2015.01.12	Washington	unknown	1	2
2016.01.22	Shanghai	neighboring shop catch fire	0	0
2016.01.26	Tokyo	something burns at vent	0	0

2.1.1 Causes of fire

The proportion of each kind of fire causes are shown in figure 1. As shown in the figure, power line failure, mechanical equipment failure, arson are the top 3 causes of subway fire, with a proportion of 26.19%, 16.67% and 14.29% respectively.

Many different electrical devices and power lines are installed in the tunnel, platform, train and station hall. Short circuit, heavy load, leakage of power or equipment failure can result in fire disaster. In order to avoid these kinds of fire, regular inspection of the equipment and power lines should be carry out, and the hidden dangers should be eliminated timely. 6 subway fire were caused by arson in these cases. In some cities, there is no security check at the entrances of subway stations. Security check is an effective way to keep flammable material such as gasoline out of a subway station. So strict security check for both passengers and luggage are suggested to set up at all the entrances of a subway stations during the important days or everyday according to the safety condition of the city.

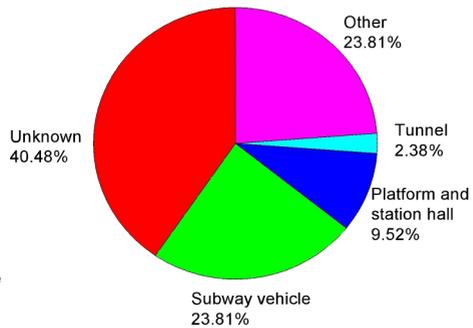
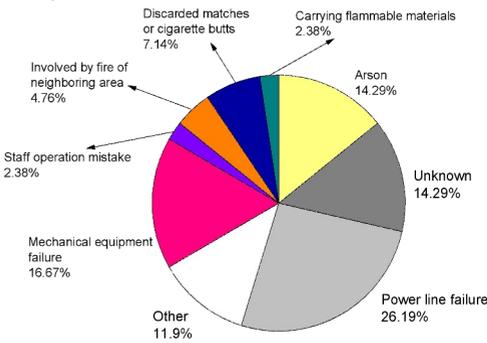


Fig. 1. Proportion of fire causes.

Fig. 2. Proportion of fire start locations.

2.1.2 Location of fire begin

The locations where fire first began in 17 out of 42 cases are unknown due to information shortage. The proportion of fire first began in tunnel, platform and station hall, subway train and other places such as warehouse are shown in figure 2. Fire first began on the train in 10 cases, account for 23.81% of all cases. Due to mechanical failure or electrical failure, some old subway trains may catch fire easily. Besides, the interior decoration, floor and seats of some old trains may not made of non-combustible material. Also the flammable material brought by the passengers may cause fire on the train. The proportion of fires started in tunnel, platform and station hall are 2.38% and 9.52% respectively, which are much less than fires began on the train. So subway train is suggested to be treated as a strict fireproof area with priority to station hall and platform.

2.2 Terrorist attack

Terrorism generally refers to the acts of violence, including bombings, assassinations, hostage-taking, aircraft hijackings or intimidation, targeting civilians and non-combatants with the aim of threatening the government and creating a climate of terror [8, 9]. The subway station is a crowded place with just several accesses to the outside, which makes the subway station an ideal place for attacks in the eyes of terrorists. The result of terrorist attack in a closed space with large number of people can be disastrous. In order to make a clear understanding to the subway terrorist attacks, analysis based on statistic were made in this paper. Subway terrorist attack cases in cities around the world from 1976-2016 are listed in table 2, and these accidents are extracted from the Database of Worldwide Terrorism Incidents [10].

Table 2. Subway terrorism attacks around the world.

Date	City	Tactics	Deaths	Injuries
1976.01.12	New York	explosives	0	0
1977.01.08	Moscow	explosives	7	37
1986.09.04	Paris	explosives	0	0
1990.07.06	London	explosives	0	0
1994.03.19	Baku	suicide bombings	14	49
1994.06.03	Baku	remote-detonated explosive	13	42
1995.03.20	Tokyo	deadly gas sarin	12	near 6000
1995.07.25	Paris	explosives	8	80
1995.08.26	Lyon	explosives	0	0
1995.10.17	Paris	explosives	0	29
1998.01.01	Moscow	remote-detonated explosive	0	3
1998.06.03	Caracas	explosives	0	0
1998.07.02	Caracas	explosives	0	0
1999.02.17	Istanbul	fire or firebomb	0	0
1999.04.11	Moscow	explosives	0	0
2000.08.20	Caracas	explosives	0	0
2000.08.23	Caracas	explosives	0	0
2001.08.02	Caracas	explosives	0	0
2001.08.14	Rome	explosives	0	0
2001.09.02	Montréal	poisonous gas	0	over 40
2002.03.02	Medellin	explosives	0	9
2002.05.12	Milan	Gas canister for the kitchen	0	0
2002.06.02	Lyubertsy	remote-detonated explosive	0	1
2002.12.01	Caracas	explosives	0	0
2003.07.16	Moscow	explosives	0	0
2004.02.06	Moscow	suicide bombings	40	120
2004.03.11	Madrid	explosives	192	2050
2004.08.31	Moscow	explosives	10	50
2005.07.07	London	suicide bombings	56	784
2006.07.11	Bombay	explosives	209	over 700
2008.11.25	St. Petersburg	explosives	3	2
2010.03.29	Moscow	suicide bombings	40	102
2011.04.11	Minsk	explosives	15	204
2014.06.25	Cairo	explosives	7	over 100
2014.09.08	Santiago	explosives	0	14
2015.12.01	Istanbul	explosives	2	1
2016.03.22	Brussels	suicide bombings	35	340
2016.09.28	Tokyo	unknown gas	0	9

2.2.1 Geographical distribution

Figure 3 shows the geographical distribution of subway terrorist attack cases. Europe include Russia is the area with the largest number of subway terrorist attacks. The frequent happening of terrorist attacks in this area has a relationship with the non-strict arms control policy, refugees' issues and illegal immigration. Few subway attacks were reported in cities of East Asia currently. However, the subway in Tokyo, Seoul, Shanghai, Beijing and Guangzhou are all very busy and crowded subway systems, and some separatist forces, cult organization and terrorist organizations are in active at present, so attentions should also be paid to prevent subway terrorist attacks in these cities.

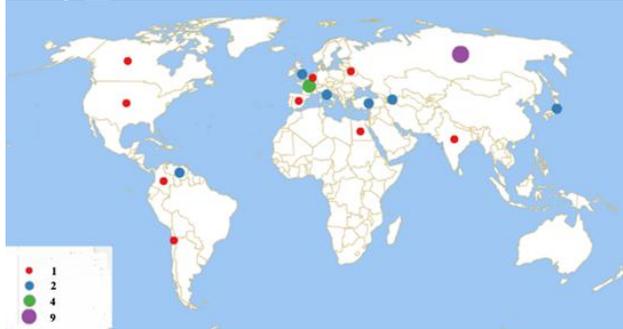


Fig. 3. Times of subway terrorist attack around the world (By country, 1976-2016).

2.2.2 Time distribution

Time distribution of the 38 subway terrorist attack cases is shown in figure 4. As can be seen from the graph, none subway terrorist attacks happened except two before the year of 1986. However, after 1986, the subway terrorist attacks gradually increased. In the 5 years during 2001 to 2005, 12 subway terrorist attacks were recorded. Subway terrorist attacks become less after the year of 2005. However, the number of subway terrorist attacks began to rise again from 2011. Terrorist attacks usually result in serious damage, so the subway station managers should be always on alert.

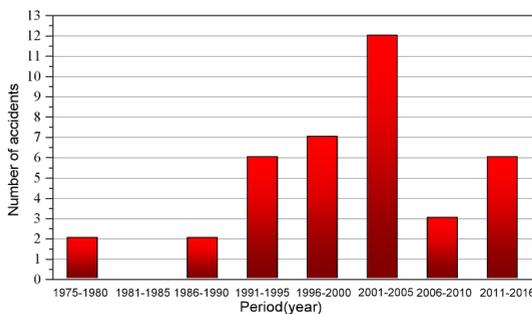


Fig. 4. Subway attacks in different time periods

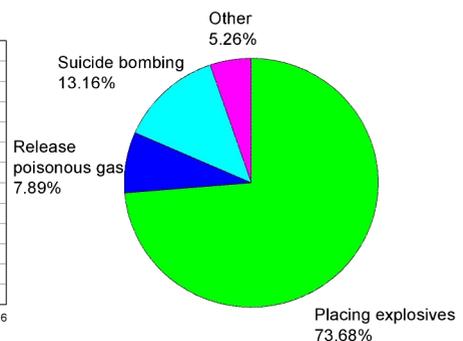


Fig. 5. Proportion of attack tactics.

2.2.3 Attack tactics

The common tactics used by terrorist include bombing, sabotage, armed attacks, arson, landmine and threat [11]. However, according to the statistics of the attack cases, placing explosives, suicide bombings and release poisonous gases are the three main types of

subway attack tactics adopted by terrorist. The proportion of each kind of attack tactics are shown in figure 5.

As described in the preceding paragraph, placing explosives is the main method of subway attack adopted by terrorists, which accounts for 73.68% of all gathered cases. Usually, explosive can cause large number of casualties and deaths in a short time, and also can make passengers fall into panic easily. Terrorist attack such as London Underground bombings in 2005 and Moscow Metro bombings in 2010 both caused dozens of death and hundreds of injuries. After the poisonous gas attack in 1995 in Tokyo metro system, some measures are taken by Tokyo metro, and after that few accidents were reported to happen in the Tokyo metro system. The measures are listed below [12]:

- Security cameras with full coverage are required to be installed in all subway stations.
- Trash cans in the subway stations should be transparent, so the contents are visible.
- The posters and broadcast are used in the subway station and train to inform passengers to ask for cooperation when suspicious objects are found.
- Security patrols are carried out by the station attendants and security guards.

2.3 Flood

In some developing countries, urban environments can be vulnerable to flood due to extreme climate and rapid urbanization [13]. Rainstorm in summer will cause flood in cities when the drainage system overloaded. Most subway stations and rails are located underground, the water can flow into the stations and tunnels through the station accesses and tunnel exits in the condition the waterproof facilities are not working well. Too much water in the station and tunnel will lead to the close of a station or even the entire subway line out of service. In early years, less attention was paid to the possibility of being flooded for subway systems, which makes some subway stations vulnerable during rainstorm [14, 15]. In order to know better about the subway flood, 13 flood accidents of subway station in different cities are collected in this paper. The time, location, causes and consequences of these accidents are listed in table 3.

Table 3. Flood accidents of subway stations around the world.

Date	City	Cause	Consequence
2001.09.17	Taipei	Typhoon	Water flew into stations and shopping area via tunnel.
2002.08	Prague	Rainfall	About 20 km of lines and 19 stations were soaked.
2004.09.09	New York	Hurricane	Water in stations, several subway lines were closed.
2007.08.08	New York	Rainstorm	The subway system heavily flooded.
2008.07.06	Beijing	Rainstorm	Line 2 out of service.
2011.06.23	Beijing	Rainstorm	Cable was soaked in rain water, causing a short circuit.
2011.08.23	Nanjing	Rainstorm	Water flew into the tunnel.
2012.07.21	Beijing	Rainstorm	Water caused the induction board work improperly.
2012.10.30	New York	Hurricane	Many subway tunnels were inundated with floodwater.
2014.08.25	Busan	Rainstorm	Some sections of line1, line2 and Line4 were flooded.
2014.08.31	New York	Rainstorm	Some subway stations flooded.
2016.05.10	Guangzhou	Rainstorm	Water flow into Changban station through entrance.
2016.07.06	Wuhan	Rainstorm	Several stations of Line 4 were flooded.

No one died or got injured in these 13 accidents. However, the operation of subway systems were affected by varying degrees in all these cases. Subway is an important transportation tool in cities, a large number of passengers travel by subway every day, so passengers' travel plan will be affected if the subway out of service due to flood. Besides, these 13 flood accidents of subway station are mainly caused by typhoon or rainstorm, so waterproof measures should be take into consideration in the design and maintenance of subway stations in cities with frequent typhoons or rainstorms. Entrances of some subway stations have the same height with the ground and no canopies were installed, during rainstorm seasons, rain and water can flow into the stations easily. In order to prevent water from entering, steps and canopies should be added at the entrances of stations built earlier.

2.4 Earthquake

Engineers generally hold the idea the earthquake has limited impact on the structures lies underground. However, during Kobe Earthquake in Japan in 1995, Daikai subway station, an underground station was almost destroyed [16]. Then researches focus on the impact of earthquake to subway station were carried out by some scholars [17-19]. According to their findings, the underground structures of subway station can be influenced by the earthquake. In other words, earthquakes can threat both the safety of underground stations, tunnels of subway system, thus the safety of passengers in the subway system is threatened. 6 cases of subway affected by earthquakes are collected and listed in table 4.

As shown in table 4, earthquake with different magnitude influence the subway systems in different ways. Usually a smaller earthquakes may only force the subway train slow down or stop. But a larger earthquake can cause the overturn of the station column, even the collapse of the whole station. Meanwhile, there are no obvious indications before an earthquake. It is often too late to get prepared when earthquake suddenly occur, thus resulting in more casualties. Subway stations usually located underground, when structures destroyed or collapsed in an earthquake, both rescue or escape are not easy. So it is necessary to get prepared before an earthquake. For example, detailed emergency plans for earthquake with different magnitude is needed, so people can get well prepared more quickly when earthquake occurs. Also, knowledge about escape in an earthquake should be popularized to the public via the poster, short video, and broadcast or other ways, so when an earthquake happens, people can make a way to escape instead of falling into panic.

Table 4. Cases of subways affected by earthquake.

Date	Location	Magnitude	Consequence
1985.09.19	Mexico city	8.1	All lines of metro were out of service.
1995.01.17	Kobe, Japan	7.3	5 stations damaged, about 3km tunnel collapsed.
2003.05.26	Sendai, Japan	7	Sendai Subway were out of service.
2014.05.11	Hualien, Taiwan	5.9	Taipei MRT were out of service.
2015.05.25	Kanto, Japan	5.6	Tokyo subway were out of service.
2015.10.26	Afghanistan	7.8	Delhi subway out of service, some people trapped.

2.5 Stampede

When something unusual happen in a subway station, such as earthquake or violent incidents, passengers may fall into panic and then try to escape. If there are too many people in a station, a stampede accident happens easily, and the control of the flow of crowd is difficult. Usually, the consequence of a stampede accident in a subway station is serious for the space is small, and economic loss and casualties can also be resulted. 15

cases of stampede accidents in subway station or on train are collected and listed in table 5. All these collected accidents happened in the mainland of China.

Table 5. Stampede in subway stations in China mainland.

Date	Stations	Events
2001.12.04	People's square, Shanghai	Too crowded, a woman fell down to the track
2007.12.21	Century Avenue, Shanghai	Too crowded, 5 people fell down on the escalator.
2009.12.21	Jiangsu Road, Shanghai	Escalator suddenly stopped and 7 people injured.
2010.08.10	Zhichunlu, Beijing	Too crowded in transfer channel, 1 person got hurt.
2010.05.26	Huaqianglu, Shenzhen	Goods fell down on the escalator.
2012.4.26	Olympic Green, Beijing	A man fell down on the escalator.
2014.03.04	Xicun, Guangzhou	Two young man play pepper spray on the train.
2014.05.09	Tiyu Xilu, Guangzhou	A fight in entrance channel
2014.06.07	Shenzhen, North railway station	A fight on the train, other people tried to escape.
2014.06.05	Guomao, Beijing	Some people quarrel in the transfer channel.
2014.06.16	Jiedaokou, Wuhan	A fight on the train and passengers tried to sheer.
2014.09.18	Line 4, Beijing	A riot was caused by quarrel on the train.
2015.04.20	Huangbeiling, Shenzhen	A woman fell down, passengers fell into panic.
2015.09.22	Zhuzilin, Shenzhen	A boy ran on the platform.
2016.05.05	Century Avenue, Shanghai	Dumbbells blocked the exit of escalator.

2.5.1 Location of stampede

Figure 6 shows the proportion of location where these stampede accidents happened. The proportion of stampede happened on the escalator is 33.33%. People are more likely to get hurt in an elevator when it is moving. 4 accidents happened on the train, accounting for 26.67% of all cases. The space on the train is smaller and the train is completely closed, so the stampede on the train also can be very dangerous. Among these accidents, two cases should be special noticed. The first one happened in Huaqianglu station, Shenzhen on May 26, 2010. In this accident, escalator was used to carry goods with large size, and the goods fell down. Another one happened in Century Avenue Station in Shanghai on May 05, 2016. A woman put dumbbells on the escalator and she try to pick it until the escalator reach the top, then the following passengers got blocked. From these two accidents, it can be seen that it is dangerous to carrying over-sized or heavy goods by escalator and such behaviors should be prohibited.

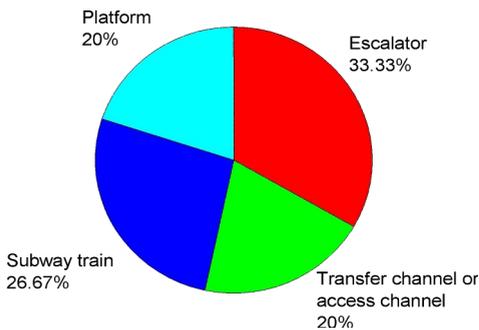


Fig. 6. Proportion of locations for stampede.

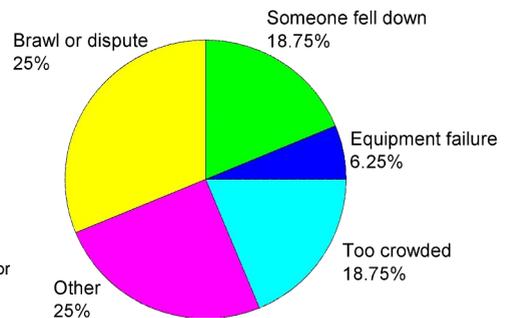


Fig. 7. Proportion of causes for stampede.

2.5.2 Causes of stampede

The proportion of stampede causes are shown in figure 7. The top three causes for subway stampede are brawl or dispute, too crowded and someone fell down. In order to avoid

stampede accidents, the following improvement are suggested to be made in public safety education and station management.

- The number of passengers in a station should be controlled, if there are too many passengers in the station, then passengers out of the station should wait to get in.
- By poster, TV or broadcast, passengers should be informed to stay calm when something happens, also the right way to escape should be informed.
- When something happens, working staff in the station should get to the scene as soon as possible and try to help solve the problem.
- Carrying oversized goods or heavy goods by the escalator should be forbidden.
- The controlling centre should monitor the whole station by CCTV, if something happens, effective measures should be taken as soon as possible.

3 Summary and recommendation

Case statistics and analysis of different kinds of natural and man-made disasters that happened in the subway stations and on the trains were presented in this paper. According to the analysis, the following conclusions can be obtained:

1. The top three causes of fire in subway stations are power line failure, mechanical equipment failure and arson. So regular inspection and maintenance work for electrical equipment should be carried out, and strict security check for both passengers and luggage are suggested to be set at the entrances of a subway station. Most fire started on the train, the train should be treat as a key fire-preventing area.

2. Terrorist attack in subway stations are frequent in recent years, and the most common tactics adopted by terrorist are placing explosives or suicide bombings. Security check, security patrol and CCTV system are useful methods or tools to prevent terrorist attack in subway stations.

3. Some old subway stations may be flooded due to the design defects, in order to avoid flooding of subway stations, canopies and steps should be installed or added at the entrances, and flood gates should be installed at the exits of tunnels.

4. Earthquake with large may destroy the station or tunnel in varying degrees. While earthquake with smaller magnitude usually make the subway station or train out of service. So different emergency plans are suggested to be formulated in order to cope with earthquakes with different magnitudes.

5. Stampede in the subway station can be a serious disaster for some subway stations are crowded. According to the case statistics, escalator is the place where most stampede accidents happened. In order to avoid stampede, safety education and propaganda to the passengers should be carried out, also the utilization of escalator should be well managed.

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