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Causes of explosion in section c of the diversion tunnel under construction at Zengwen reservoir

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ABSTRACT: A diversion tunnel project at Zengwen Reservoir, Taiwan, was made to increase its water storage. During the cleanup operation after blasting this tunnel, flammable vapor clouds leaked from the rock drums and sunk down to where they contacted with a flammable source and exploded. This research conducted field investigations to assess the course of the accident and the scene after the explosion, while collecting oil and gas samples inside and from a nearby tunnel in order to undergo Gas Chromatography-Mass Spectrometer (GC-MS) analysis. By comparing the samples from different sections of the diversion tunnel, results showed that large amounts of flammable gases, light oil, and medium oil were inside the tunnel when it exploded. The application of GC-MS during investigation is crucial in the identification of material compositions. In addition, the top portions of the tunnel contained dead spaces where flammable gases could accumulate and reach explosion limits.

1 INTRODUCTION

Tunnels are a type of underpass which is mostly made for pedestrians, scooters, and general road and railway transportation. Nonetheless, some are made to transport water or have other specific purposes. Therefore, development of tunnels is beneficial for transportation convenience.

If flammable gases are released during construction of a tunnel, it could result in a fire or explosion. To avoid accumulation of hazardous gases inside tunnels, ventilation methods must be used to exhaust the gases. The Tunneling Association of Japan recommends that the wind speed inside tunnels be at least 0.5 m/s, while the ventilation design should allow the wind speed to be maintained at 1.0 m/s or higher in order to effectively prevent hazardous gases from accumulating at the arches of tunnels. If methane was to exist inside tunnels, the concentration should be lowered to 1.5% or lower (Ho 2004).

For measuring flammable gases, specified personnel should enter the tunnel every day before operation, after an earthquake, or any other scenario where there may be flammable gas leakage. Fixed automated detectors and portable detectors should both be used, and portable detectors should be used two to three times each day, while measurements should be repeated twice or thrice each time to ensure correct values. When choosing between detectors, the detection range and limitations of the instruments should be noted, while other factors in the environment which could affect detection should also be noted. Besides increasing the gas detection time and area, personnel advocacy and verification, equipment safety control, and personnel training, simple and convenient portable detection equipments should be provided to enhance efficiency of the people working on site, while also strengthening automated examinations (Wang 1998).

For the effect of explosions on pressure waves, Pang et al. (2014) used experiments and numerical simulations to propose the changes in shockwave overpressures against increasing distances for a methane pipe explosion. The trends are increasing overpressure values for increasing distance within 100 meters, and vice versa when the distance is more than 100 m. The flames and pressure waves caused by explosions produce temperature heat, which is one of the main hazards inside tunnels. Zhang & Ma (2015) reported that pressure waves caused by explosions can be divided into static pressure and dynamic pressure; the high-speed flow caused by gas burning is classified as dynamic pressure. At the tunnel entrance, the hazard of dynamic pressure far exceeds that of static pressure, while wind caused by air flow also results in serious damage. Experiment results by Zhang et al. (2013) showed that the more branches a tunnel contains, the larger the overpressure values. This scenario can be observed during the construction of a tunnel, when a construction adit is created beside the main tunnel construction area, which accelerates the overall process. Tian et al. (2011) used numerical methods to show that for a tunnel with one end open and the other closed, the explosive field would be reflected by the closed side of the tunnel, which would result in a catch-up effect and overlapping with the other pressure waves, thus causing a larger explosion than if the tunnel was open on both ends. Tunnels which have one end open and the other closed are common among tunnel construction projects. A research conducted by Sasmito et al. (2013) indicated that adequate flow designs can enhance gas control whilst maintaining a low pressure drop. Furthermore, additional auxiliary ventilation also enhances gas control during tunnel constructions, which can be used as reference when designing the ventilation system for a tunnel.

The diversion tunnel construction at Zengwen reservoir is for the solving of water supply in southern Taiwan. Extra water, during the wet period of Laonong river and a tributary of Gaoping river (both rivers located in Kaohsiung and Pintung counties, Taiwan), is stored in the Zengwen reservoir, thus increasing the inflow of the reservoir and increasing the utilization of the dam and its water storage. However, the explosion which occurred during the construction was so powerful that it blew a truck parked at the tunnel entrance 10 meters out, subsequently killing two workers on November 4, 2007. This research collected oil samples and conducted assessments of the course of the accident and the scene after the explosion. A more complete inspection led to uncovering the cause of the explosion, which then could be the baseline to establish standards so as to lower chances of accidents while increasing the efficiency of the construction of the diversion tunnel (Lee et al. 2009).

2 RESEARCH METHODS

During the construction of the Zengwen reservoir diversion tunnel, an explosion occurred and initial assessment results indicated a gas explosion. To find the reason which caused the accident, this paper used the methods mentioned below.

2.1 *Field investigation*

This research conducted a field investigation of the tunnel site, while also asking the engineering staff about the on-site construction, ventilation system, gas detection, and project management, so as to assess the flammable gas accumulation situation and location of ignition, and further discover the reasons for the explosion.

2.2 *Use of GC-MS to analyze the gas and liquid leakage in the tunnel*

Gas Chromatography (GC) is conducted by injecting the sample directly into the column or by heating the sample after it has entered the column. The column is heated linearly or controlled by programs, while the carrier gas and stationary phase of the components would have differing distributions based on their thermodynamic properties (vapor pressure of compound under chromatograph temperature and selectivity of stationary phase). The carrier gas would carry the compound vapor through the column, and the components would be separated based on the varying vapor pressures and selectivity of stationary phases.

The GC detector used in this research was a Flame Ionization Detector (FID) and Thermal Conductivity Detector (TCD). The Flame Ionization Detector burns H_2 in O_2 to create flames, so when the sample ionizes within the flames (ionization), an ion current is formed under an electric field, and they are gathered at the electrode to create an electric current which is then detected. The basis of TCD is when an analysis is present, the thermal conductivity of the airflow changes and is detected.

The basis of MS (Mass Spectrometer) is the production of ions that are subsequently separated or filtered according to their mass-to-charge (m/z) ratio and detected. The resulting mass spectrum is a plot of the (relative) abundance of the produced ions as a function of the m/z ratio.

The Gas Chromatography-Mass Spectrometer (GC-MS) is an instrument which combines the separation capabilities of GC and differentiating abilities of MS; the component vapor separated by GC is sent into MS to obtain information on molecular structure.

During on-site investigation of the tunnel, unknown gases and liquids were found seeping through the ceiling, walls, and floor of the tunnel. After they were collected, composition analysis was accomplished by using GC-MS to confirm the existence of flammable materials inside the gases and liquids.

The gas chromatograph used was model HP-6890 N, while the mass spectrometer was model FIONS PLAYFORM II; chromatography column was 60 m long, film thickness was 0.25 um, inner diameter was 0.25 mm, analysis duration time was 110 min, temperature of injector was 310°C, mobile gas phase was helium, and linear flow rate was 1 mL/min.

3 RESULTS AND DISCUSSION

The situation inside the tunnel was given by on-site investigation, as shown in Figure 1 with two deaths found in the tunnel. Based on the burning of the equipment at the accident scene and the blown truck at the tunnel entrance, it was determined that the cause was a gas cloud explosion.

In order to uncover the cause of this accident, the location of the fire source had to be found first. A truck inside the tunnel (Fig. 1) had its shifter (gear lever) at the top position as shown in Figure 2, meaning that it was parked, thus proving it was turned off and therefore not the source. A BH120 excavator was found turned on with its lights on during the rescue of people from the accident; also, Figure 3 shows that the key in the excavator was in the "On" position, proving that it was the fire source of the explosion.

After determining the fire source, the accumulation of flammable gases was next. The tunnel possessed a ventilation system and some fixed gas detectors while personnel used handheld instruments to measure the gas concentration; nevertheless, an explosion still occurred, which is why this investigation focused on the ventilation and gas detection inside the tunnel.

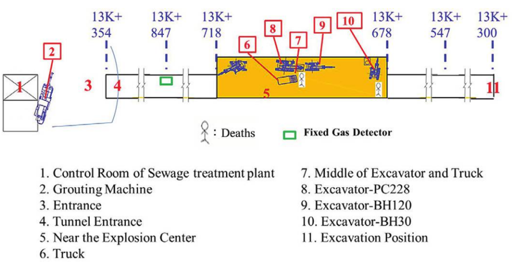

Figure 1. Situation inside of the tunnel.

Figure 2. Truck inside tunnel with shifter at the top position.

Figure 3. BH120 excavator with the key in the "On" position.

3.1 *Situation of ventilation and gas detection inside tunnel*

After interviewing the workers on-site, it was recognized that hazardous gases would continuously be monitored during drilling and that flammable gas detectors (fixed automated detectors) shown in Figure 1 were installed at heights of 1.8 m inside the tunnel, with all of the measured values being lower than the permitted concentration. During the blasting operation of the construction, blowers at the entrance would provide ventilation after blasting. An on-site engineer (specified personnel) pairing with non-periodical measurements used a four-in-one gas detector (portable detectors) and detected hazardous gases from the tunnel entrance to the digging location at about 500 m away, with the height of detection at 1.3–1.6 m.

Due to influence of the air flow on the flammable gases, some of them lingered at the top of the tunnel which was 5.8 m high; the on-site personnel could not effectively measure the concentration of hazardous gases, resulting in detection values far lower than the lower explosive limits. When the gas cloud gradually spread from the top of the tunnel to the bottom, the flammable gases exploded as it came into contact with the fire source, which in this case was the starting induced by the BH120 excavator.

Investigation found that even under ventilation conditions, flammable gases could still accumulate at the arch of tunnels; even if the gases were heavier in density than air, they could still spread with the air flow, while uneven distribution would inhibit effective detection. This is why the measured gas concentrations near the floor were all lower than the legal standard concentrations.

After the explosion, unknown gases and liquids were found seeping through the ceiling, walls, and floor of the tunnel; this research collected them and used GS-MS for composition analysis to determine the possibility of flammable gases leaking through the rocks in the tunnel.

3.2 *Gas and liquid composition analysis*

After the accident, locations 13 K and 300~400 m had cracks in the floor which were seeping unknown gases and oils. These were collected and analyzed, with the results arranged in Table 1.

The gases were analyzed using GCFID, with results showing in Table 2 that methane was the most at 844,535 ppm, and by using GCTCD, as listed in Table 3, methane occupied up to 94.86%, which means that large amounts of methane gas was leaking from the rocks. Methane is flammable and is lighter than air and floats upward easily which allowed it to accumulate at the arch of the tunnel 5.8 m above the floor. The gas detectors installed in the tunnel were at a lower position (1.8 m) while the handheld devices used by engineers were also used at lower heights (1.3~1.6 m), resulting in ineffective measurements. Methane would proceed to accumulate, and then exploded when a fire source was presented.

Table 1. Gas and oil samples in tunnel at locations 13 K and 300–400 m.

Location	Sample	Layer of exposure	Ignited or not
West tunnel 13 K + 300~400 m	Cracks in floor with bubbles	Limestone layer	ND

Table 2. GCFID analysis.

No	Substance	Concentration (ppm)
1	Methane	844,535.00
2	Ethane	31,669.70
3	Propane	3,544.18
4	iso-butane	501.32
5	n-butane	206.53
6	iso-pentane	52.65
7	n-pentane	9.79
8	n-hexane	1.61
9	n-C7	1.71
10	Benzene	34.77
11	n-C8	3.07
12	Toluene	28.19

Liquids were collected from two locations, one was a dark brown oil slick at 13 K + 300 m, which was analyzed by GC-MS and produced the total ion chromatogram labeled in Figure 4; the other was a dark brown suspended emulsion at 13 K + 340 m and its GC-MS results are shown in Figure 5.

The analysis of the oils from two locations at 13 K + 300 m and 13 K + 340 m were compared with a standard result from a mixture of gasoline and diesel fuel as shown in Figure 6.

Table 3. GCTCD analysis.

No	Substance	Percentage (%)
1	C5 = /C6+	0.0105
2	Carbon dioxide	0.2405
3	Propane	0.2177
4	i-Butane	0.0307
5	Ethane	3.4852
6	Propadiene	0.0005
7	n-Butane	0.0131
8	i-Pentane	0.0033
9	Oxygen	0.3227
10	Nitrogen	0.8144
11	Methane	94.8616

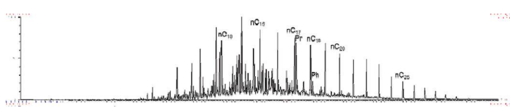

Figure 4. GC-MS results at 13 K + 300 m of tunnel.

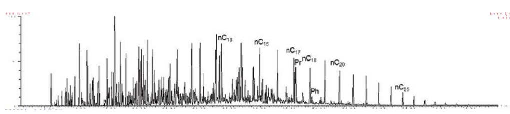

Figure 5. GC-MS results at 13 K + 340 m of tunnel.

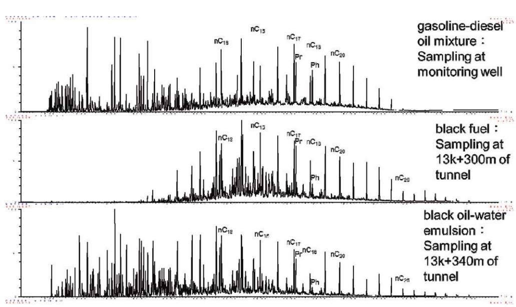

Figure 6. Composition comparison at 13 K + 300~400 m of tunnel.

Comparisons showed that the sample contains light oil and medium oil; also, oil collected inside the tunnel before the accident also contained light oil and medium oil, meaning the rocks in this tunnel contained flammable liquids besides flammable gases, which volatilized into flammable vapors that contributed to the explosion.

Based on the composition analysis from the scene, the rocks in the tunnel contained methane and ethane amongst other gases, and also light oil and medium oil amongst other liquids, which are all flammable substances, therefore being judged as the source of the explosion. From this case, the importance of using GC-MS and other equipment for composition analysis can be noted. In the future, chromatograms of oils and flammable gases should be established for the convenience of comparing the type of leaked substance if a tunnel explosion was to occur.

4 CONCLUSION

GC-MS analysis results of samples inside the tunnel showed that the tunnel contained large amounts of flammable gases along with light oil and medium oil. Methane posed as the majority, while the total of methane and ethane alone took up near the totality of all the gases combined. This shows that the rocks in the tunnel are filled with hazardous gases; when leaked into the tunnel and mixed with air, it produces a gas cloud explosion when upon contact with a flammable source. These results show that careful sampling and the use of GC-MS for comparisons can confirm the actual reasons for the accident.

This accident resulted from leaking flammable gases after excavation, which could have been a mixture of methane, toluene, xylene, and other flammable vapors. Surveying for flammable hydrocarbons before construction to ensure safety during excavation is required. Monitoring the concentration of hazardous gases during construction should also be considered, while fixed instruments should be used along with handheld instruments. Tunnels sections top, middle, and bottom and left, middle, and right should be measured, while the height should reach the tunnel arch; calculations should also be done for the detection delay time when the probe is touching the ceiling so as to ensure the validation of the measurements. Gas measurements have to be conduct periodically to avoid any negligence; if unknown leaking gases or liquids are detected, instrumental analysis should be conducted immediately to confirm the compositions of the gases or liquids, and corresponding protective measures and ventilation should be executed to ensure construction safety.

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REFERENCES

Ho, T.Y. 2004. Investigation and countermeasures during encounter of flammable gases in tunnel construction. *CECI Engineering Technology* (63).

Lee, B.C., Shu, F.Y. & Chen, M.C. 2009. Explosion disaster prevention for tunnel projects based on explosion case of diversion tunnel construction plan for Zengwen reservoir. *Industrial Safety and Health* 244: 48–57.

Pang, L., Wang, T., Zhang, Q., Ma, Q. & Cheng, L. 2014. Nonlinear distribution characteristics of flame regions from methane–air explosions in coal tunnels. *Process Safety and Environmental Protection* 92(3): 193–198.

Sasmito, A.P., Birgersson, E., Ly, H.C. & Mujumdar, A.S. 2013. Some approaches to improve ventilation system in underground coal mines environment–A computational fluid dynamic study. *Tunnelling and Underground Space Technology* 34: 82–95.

Tian, C.M., Wu, Y.B. & Lo, C.F. 2011. Characteristics of in-tunnel explosion-induced air shock wave and distribution law of reflected shock wave load. *Journal of Vibration and Shock* 30(1): 22–26.

Wang, S.L. 1998. Accident analysis–How to reach the goal. *Labor Safety and Health Newsletters* (27): 15–17.

Zhang, P., Du, Y., Zhou, Y., Qi, S., Wu, S.L. & Xu, J.F. 2013. Explosions of gasolineeair mixture in the tunnels containing branch configuration. *Journal of Loss Prevention in the Process Industries* 26(6): 1279–1284.

Zhang, Q. & Ma, Q.J. 2015. Dynamic pressure induced by a methane–air explosion in a coal mine. *Process Safety and Environmental Protection* 93(): 233–239.