Accident analysis and safety assessment for tunnelling works

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Accident Analysis and Safety Assessment for Tunnelling Works

Analyse des accidents et sécurité dans la construction de tunnels

Unfall-Analyse und Sicherheits-Beurteilung im Tunnelbau

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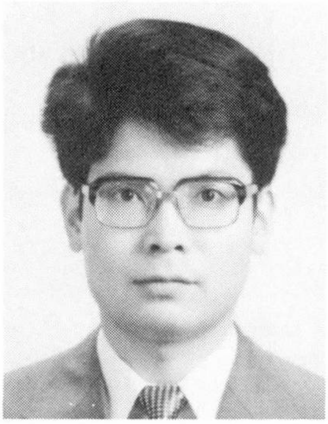
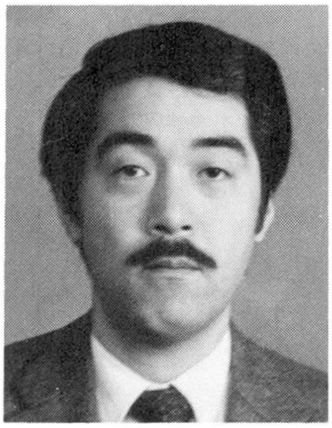




SUMMARY
This paper presents labour accident analyses of large construction projects for the purpose of clarifying a basic understanding of accident situations on construction sites. A guideline of the safety assessment for tunnelling work is proposed to set up precautions at the stage of execution planning, prior to the initiation of the work, in order to prevent accidents during the construction stage.

RÉSUMÉ
Le rapport présente l'analyse d'accidents dans de grands chantiers de construction afin de mieux comprendre cette situation fondamentale des accidents du travail. Les grandes lignes d'une méthode d'évaluation de la sécurité pour la construction de tunnels sont présentées dans un but de prévention des accidents du travail, déjà lors de l'élaboration du projet.

ZUSAMMENFASSUNG
Der Beitrag beschreibt zunächst die Untersuchung von Arbeitsunfällen auf grossen Baustellen, um die Verhältnisse klarzulegen. Dann werden Richtlinien für die Sicherheits-Beurteilung im Tunnelbau gegeben, damit schon im Entwurfsstadium Arbeitsunfälle verhindert werden können.

1. INTRODUCTION

Every year a lot of casualties take place in the construction industry. Recently labour accidents associated with construction work account for about one third of all occupational accidents and represent nearly a half of the number of deaths for all industry in Japan. Labour accidents also constitute a major cause that downgrades the construction production with direct and indirect financial losses. Therefore, prevention of labour accidents is one of the important issues in safety and quality assurance in the area of construction work.

This paper presents 1) labour accident analyses of large construction projects for the purpose of clarifying a basic understanding of accident situations in construction sites, and 2) A guideline of the safety assessment for tunnelling work, to set up precautions at the stage of execution planning, prior to the initiation of the work, in order to prevent future accidents during the construction stage.

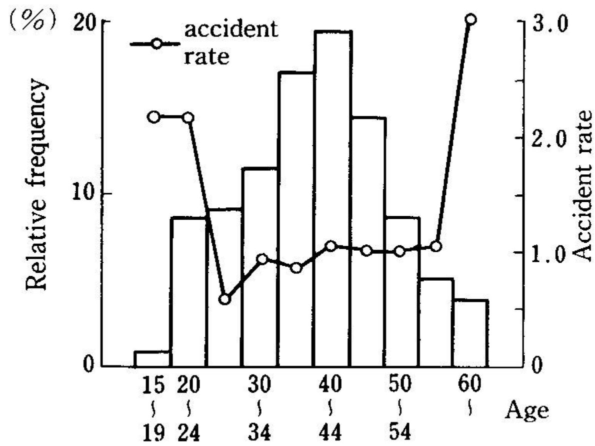
2. ANALYSIS OF OCCUPATIONAL ACCIDENTS IN CONSTRUCTION WORK

Two large bullet train construction projects were selected for the analysis in this study. 1) The New Sanyo Rapid Trunk Line (from Okayama to Hakata ; 444km length ; construction period 1967−1975), and 2) The New Joetsu Rapid Trunk Line (from Omiya to Niigata ; 304km length ; 1972−1982). These two projects cover various types of structure construction work, such as tunnels, bridges, etc. .

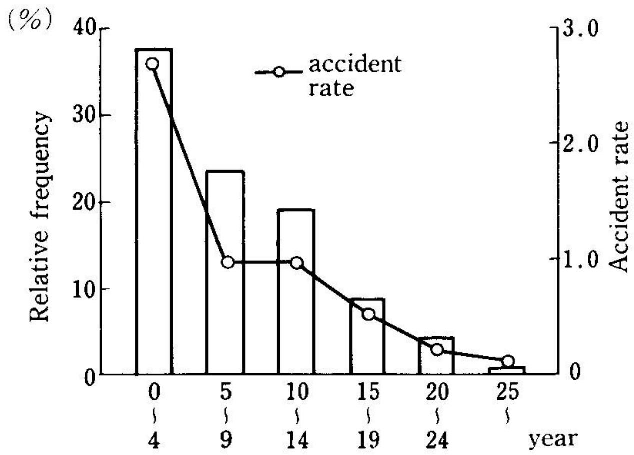
Available accident data (Industrial accident reports) were collected from prefectural labour standard offices involved. These data totaled in number 1868 injuries, including 55 deaths in the New Sanyo Line construction work, and 2055 casualties including 84 fatalities in the New Joetsu Line construction work.

2. 1 Accident situation of personnel [1]

To throw light on the nature of labour accidents in construction sites, various statistical analyses were carried out. Here, an analysis on the accident situations of personnel is presented. Fig.1 and Fig.2 show the distribution of accidents in the New Sanyo construction work, analyzed by age and years of exprience of the injured personnel. Both figures also contain the relative accident frequency rate (ratio of the proportion of accidents to the proportion of workers in each cell). As illustrated in these figures, accidents are concentrated in the middle age groups and inexperienced personnel. From the relative accident frequency rate, accidnts are more liable to occur in young and elderly personnel, which is 2 or 3 times higher than the average rate. As shown in Fig.2, accidents are less likely to happen in accordance with the increase in work experience. This statistical tendency could also be found in the anaysis of the New Joetsu construction work accidents. A notable difference between the accidents of the two projects is that the average age and the experience years of injured personnel in the Joetsu project (41.0 old, 10.4 years) were higher and longer than those of the Sanyo's (39.9 old, 7.1 years), which reflects the fact of the aging of work population in this industry.



Fig・1 Distribution of age of personnel



Fig・2 Distribution of years of experience

2. 2 Multivariate analysis of accidents in tunnelling work [1]

Various multivariate analysis methods were applied to the study of the basic relation between labour accidents and tunnel construction site characteristics. The tunnels under investigation in this analysis are those in the New Sanyo construction project belonging to Hiroshima and Yamaguchi prefectures, which were 75 sites in number. Depending upon the construction project record compiled by Japan National Railway, the available data on site's characteristics involved in the analysis were collected, viz: 13 kinds of numerical variables (eg. tunnel length, construction periods, rock grade index, total excavation hours consumed, etc.), including the number of accidents, and 3 kinds of categorical data such as method of excavation, transportation system, and of types of entrance approach.

After compiling these data for all the sites, 12 numerical variates in each site were divided by the tunnel length to make these variables comparative between each site. In order to find outliers in these normalized data, the 3rd moment (skewness) and 4th moment (kurtosis) of these variables were used. This detecting resulted in 6 sites that had some discordant values with respect to the construction variables. Therefore, for the purpose of assuring homogeneity of the data structure, variables in these 6 sites were excluded from the data set, so that the final number of construction sites for the analysis was 69.

The main results obtained in this analysis are pointed out as follows :

1) From the correlation analysis, there is a strong correlation between total number of accidents and the total volume of construction materials consumed. However, the accident frequency rate (the number of accidents per 1 km) has no positive relation to the volume of the construction variables concerned. In contrast to the overall accident frequency rate, the fatal accident frequency rate decreases in accordance with the increase of the volume of construction variables. This rate also depends upon the individual geological characteristics of the strata of the particular construction site.

2) According to the principal component analysis, many selected numerical variables can be explained by a few factors such as the size of construction work, the geological factors of tunnel, and the labour accident factors. (See Table 1) Since accidents constitute a major component in the analysis, statistical evaluation between work sites with reference to accident can be achieved by making use of the accident frequency rate. The Poisson distribution also could be employed for the statistical analysis of the number of occurrences of accidents in a site.

3) A discriminant function was developed to distinguish with high accuracy whether or not a work place may have fatal accidents during its construction periods. From this analysis, fatal accidents are more likely to occur in a workplace where the geological conditions are relatively better, and the execution of the construction work was accomplished within a short period of time. Interpretation of the variables employed in the proposed discriminant function were explained similar to the ones given in the correlation and the principal component analyses.

4) Also a multiple regression equation was proposed to predict the number of occurrences of accidents in a construction site with a relatively high multiple correlation coefficient. Total volume of steel arches erected, method of excavation, and index of rock grade have played an important role for establishing the regression equations. These explanatory variables could also give the same implications of the accident situation as revealed in the preceding analysis.

Table 1 Principal Component Anaysis of Tunnel Construction Work

Principal component	1	2	3	Accumlated contribution
Eigen value	8.4313	2.2968	0.5980	
Contribution	0.6486	0.8252	0.8712	
Number of accidents	0.7741	0.0818	0.5073	0.8632
No.of fatal accidents	0.7110	−0.1620	−0.1666	0.5595
Tunnel length	0.9719	−0.0896	−0.1308	0.9697
Construction period	0.7891	−0.0228	−0.1486	0.6453
Construction cost	0.9762	0.0658	−0.0658	0.9617
Excavation time	0.9644	0.0664	−0.1654	0.9619
Rock grade index	0.5072	−0.7503	0.2051	0.8623
Number of arches	0.9707	0.1057	−0.0896	0.9615
Volume of arches	0.8800	0.3389	−0.0558	0.8924
Volume of concrete	0.9763	0.0412	−0.1470	0.9764
Volume of invert	0.2848	0.8918	0.1190	0.8905
Invert proportion	−0.4369	0.8649	−0.0343	0.9401
Electricity	0.8228	0.1119	0.3897	0.8414
Notice	Scale	Geology	Accident	

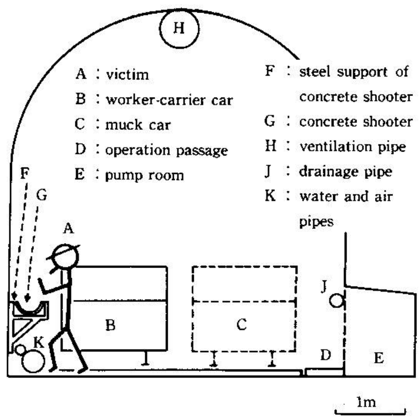
2. 3 Causal Tree Analysis of accidents in construction work

Understanding in total, the tendency of labour accident which occurred in two bullet train construction works, it is also necessary to study about each labour accident as individual cases. It is commonly recognized that there are many factors which contribute to the occurrence of labour accidents, and that these factors constitute various combinations and concatenations in the process of the occurrence of each labour accident. Therefore in order to establish the effective safety measures, it is necessary to examine in detail the process leading to each labour accident.

For the purpose of analyzing the process of the occurrence of labour accidents, 234 labour accidents that occurred in the constructin work of the New Joetsu rapid trunk line were selected. The selected samples of labour accidents were examined by means of adapting the C.T.A.method [3~5] . This is an a-posteriori method of analysis of accidents taking the passage of time into consideration. This method is regarded as a useful approach to predicate clearly and facilely the process of occurrence of an accident ; particularly concerning the relationships between various contributive factors to the accident.

In this section, in order to describe the process leading to an accident graphically, the C.T.diagrams for each accident were drawn out. The C.T.diagrams are made up by indicating events which contributed the occurrence of an accident, and by connecting these events in three kinds of connection types : sequence type, disjunction type, and conjunction type. As an example, one of these C.T.diagrams is exhibited in Fig.3. Then the linkages of events in the C.T.diagrams were investigated, one by one, each diagram with reference to the factors which might contribute to the occurrence of the accident. These contributive factors were identified and classified into five categories shown below :

- I (human, individual) factor ; factors relating with persons concerned (ex. unskillfulness, fatigue)
- T (task) factor ; factors relating with work/task concerned (ex. operation at a high elevated place)
- M (material) factor ; factors relating with machinery/ equipment/tool (ex. breakdown, dangerous tool)
- Ep (physical environment) factor ; factors relating with working place/environment (ex. climate)
- Es (social environment) factor ; factors relating with organization/management (ex. control, planning)



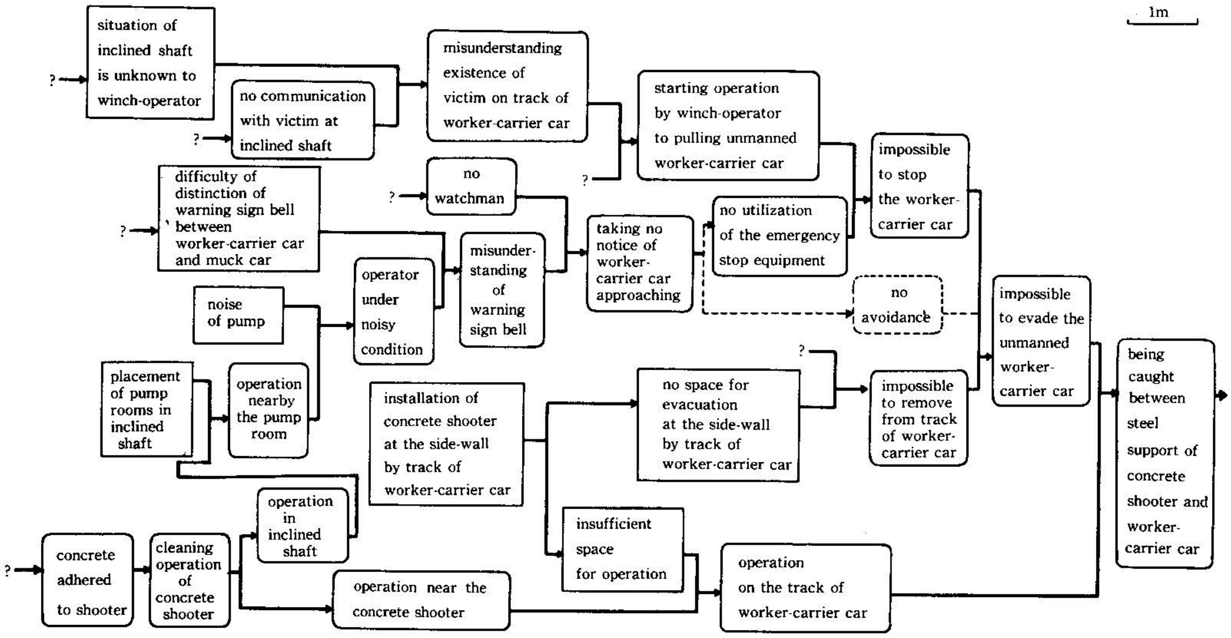


Fig. 3 C.T. diagram of an accident

Table 2 Typical interrelationshipes between contributive factors to accidents in construction works

		Subsequent factor I	Subsequent factor T	Subsequent factor M	Subsequent factor Ep	Subsequent factor Es
Previous factor	I	difficulty of communication between individuals (ex. default sign) etc	operation disturbance by improper behavior (ex. unskilled worker) etc	improper use of machinery/tools etc	influence for working condition by behavior of individual etc	disturbance in organization
	T	dangerous works (ex. operation at a high elevated place) etc	inadequate adjustment between concurrent operation etc	improper task assigned to machinery/equipment etc	influence on working condition by inadequate operation mode etc	confusion of working crew due to changing operation mode etc
	M	insufficient protection of worker from machinery etc	disturbance in operation by using improper tool/equipment etc	mismatching use of machinery and material etc	influence on working place by using machinery (ex. vibration) etc	confusion of working crew by using new-machinery etc
	Ep	un-hygienic working place etc	disturbance in operation by working condition (ex. inadequate lighting) etc	environmental effect on machinery/equipments (ex. humidity, heat) etc	environmental effect on working place(ex. decrease stability of sloop by rain) etc	delay the work due to climate condition etc
	Es	Inadequate management system in communication etc	Allowing inadequate work mode etc	absence of person in charge of examining machinery etc	work areas left in a disorderly fashion etc	disorganization due to inadequate adjustment between working crews etc

In accordance with the definition of classification of these five contributive factors, the frequencies of the factors leading to labour accidents, and the relationships between the factors were investigated. The description of the relationships between the five contributive factors were arranged and illustrated in a table (Table 2). One of the purposes of this arrangement is to consider dynamically the characterization of the factors; for instance, the factor generally called "human-factor" has varied significance. So it is necessary to treat the effect of the human-factor on other factors, and the influences of other factors to the human-factors. Though this table seems unable to indicate exactly the facts which bring the risks to the construction field, it is very helpful in obtaining a new understanding of the malfunctions inherent to a certain situation of the construction field, and very useful for considering specific prevention measures against labour accidents in the future.

By making use of the results of C.T.A., the process leading to accidents which occurred in the New Joetsu construction work was compared with accidents in another type of work (cutting works of road-constructing), and was examined from the point of the differences of the five structures constructed (tunnel, bridge, overhead railway, rail installation, and others), of the four types of accidents (falling, flying objects, machinery, and cave-in), and of the nine supervisory contractors ; symbolized A~H and J in this study. The results of examination are presented as "the distributions of the frequency of contributive factors to accidents" and as "the influential transition matrices" which means the situations of reciprocal actions between five contributive factors to accident.

The distributions of frequency of contributive factors to accident are shown in Table 3. From this table, it can be seen that T (task) and M(material) factors were the predominant factors to accidents in the New Joetsu construction work. When compared with another type of construction work, the New Joetsu construction work did not have the same proportion of frequency of the five factors. Particularly, M (material) and Ep (physical environment) factors were different in the two types of work. So far as the types of accident concerned, the distributions of the frequency of the contributive factors were slightly different each other.

Table 3 The distribution of the frequency of contributive factors to accident

Item			Sample number	I	T	M	Ep	Es
New Joetsu construction work	Total		234	14 %	41 %	33 %	9 %	2 %
	types of accident	falling	14•	27	38	25	9	2
		flying object	14•	21	50	17	8	4
		machinery	20•	11	42	40	5	2
		cave-in	5•	13	47	13	20	7
	supervisory contractors	A	37	12	44	27	16	1
		B	24	16	36	38	8	1
		C	21	11	41	37	10	1
		D	19	13	43	34	8	2
		E	27	20	42	29	6	3
		F	22	16	35	34	13	2
		G	15	21	42	30	6	1
		H	35	16	38	31	14	1
		J	34	16	30	46	6	2
	structures constructed	Tunnel	159	13	37	37	12	2
		Bridge	16	20	45	29	6	0
		Overhead railway	41	22	41	30	6	2
		Rail installation	9	22	37	32	5	3
		Others	9	22	40	32	5	2
Cutting works of road-constructing	Total		82	7	38	13	34	9
	types of accident	sloop-failure	50	2	43	5	41	9
		machinery	32	15	28	29	20	7

(• selected only representative samples)

Concerning the relationships between contributive factors, a total result of examinations of 234 accidents which occurred in the New Joetsu construction work is shown in an influential matrix (Table 4). Other matrices were also obtained in accordance to various points of difference ; types of work, types of accident, surpervisory contractors, and types of the structure constructed. (Tables are omitted for want of space.) The similarities between these matrices were examined numerically by the chi-square test and cluster analysis, these results are shown in Table 5. A similarity could not be found between the four matrices according to the different types of accidents. When comparing the nine different supervisory contractors, the similarity between matrices could not be verified. When making a comparison between the five matrices according to different structures constructed, the existence of the similarity was confirmed. As contrasted with another type of work (cutting-works of road-constructing), the influential transition matrix of the New Joetsu construction work is clearly different.

These results suggest the necessity of speific measures taking care of each different type of labour accident concerning to its own projects.

Table 4 The influential transition matrix (Total results of 234 samples of the New Joetsu construction work)

		Subsequent Factor				
		I	T	M	Ep	Es
Previous Factor	I	0.60	0.09	0.26	0.01	0.04
	T	0.19	0.53	0.24	0.04	0.0
	M	0.14	0.18	0.63	0.04	0.0
	Ep	0.25	0.15	0.36	0.24	0.0
	Es	0.17	0.57	0.17	0.09	0.0

Table 5 The similarity between influential transition matrices

Matrices considered	Number of matrices compared		Result of similarity
Classified by works	2	New Joetsu construction work, Cutting works of road-constructing	different
Classified by types of accident	4	New Joetsu construction work; falling, flying object, machiney, cave-in	different
	2	Cutting works of road-constructing sloop-failure, machinery	different
Classified by supervisory contractors	9	New Joetsu construction work; supervisory cotractors symbolized A～J	not specified
Classified by structures constructed	5	New Joetsu construction work; tunnel, bridge, overhead railway, rail installation, others	similar

3. SAFETY ASSESSMENT FOR TUNNELLING WORKS

According to the analysis of causes of the accidents in tunuel construction work, there exists some cases where safety precautions at the stage of work planning seem to have been inadequate. Therefore, in order to assure safe execution of work, a comprehensive checking system for setting up the precautions at the stage of work planning prior to the initiation of work, which we will call here "safety assessment" would play an important role for prevention of future accidents in the construction stage. The basic concept of the "safety assessment" is very close to the one that emerged from system safety engineering where the emphasis is placed upon the "before the fact" concept, identify/analyse/prevent, rather than the traditional "after the fact", accident/investigation/fix concept. [6]

With this thinking in mind, development of the safety assessment procedure was carried out. The developed system here is a process to check the necessary safety measures against all anticipated accidents by predicting the potential risk inherent to the tunnel construction site's characteristics. The developed procedure of safety assessment is described as follws :

1) Collection of basic data (lst step)
At this step, basic materials and data necessary to perform the safety assessment of tunnel construction are collected and compiled. Typical of these are the following groups : a) geolgical and geographical maps, survey

Table 6 Safety measures for basic matters

<table>
<tr><th>Basic matter</th><th>Details of assessment</th></tr>
<tr><td>(1) Work control organization</td><td></td></tr>
<tr><td>1) Chief engineer on supervisory engineer</td><td>○ Assign a chief engineer or a supervisory engineer with sufficient experience and knowledge in tunnel construction to the construction site.</td></tr>
<tr><td>2) Management organization (regulations)</td><td>○ Prepare control organization regulations specificaiiy prescribing duties for all members including subcontractors.</td></tr>
<tr><td>3) Selection of subcontractors</td><td>○ When selecting subcontractors, consider past work results and safety results.</td></tr>
<tr><td>(2) Safety and health management</td><td></td></tr>
<tr><td>1) Safety and health management system</td><td>○ Appoint the following:
<table>
<tr><th>Controller</th><th>Worksite covered</th></tr>
<tr><td>General safety and health supervisor</td><td>Worksite employing not less than 100 workers usually</td></tr>
<tr><td>Safety supervisor</td><td>Worksite employing not less than 50 workers usually</td></tr>
<tr><td>Health supervisor</td><td>〃</td></tr>
<tr><td>Industrial physician</td><td>〃</td></tr>
<tr><td>Overall safety and health controller</td><td>prime contractor's worksite where 30 or more workers including subcontract workers work at the same place</td></tr>
<tr><td>Master safety and health supervisor</td><td>Worksite requiring appointment of a general safety and health controller</td></tr>
<tr><td>Safety and health controller</td><td>Contractor for other than worksite requiring appointment of a general safety and health controller</td></tr>
</table></td></tr>
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results of environment and climate of the working site. b) documents of design, schedule, working plan, temporary work, equipments. c) work record of similar type tunnel construction or other structures constructed nearby. d) safety and health law and other related laws and ordinances, various safety technical guides and practice.

2) Check the basic matters (2nd step)
At this step, examine as to whether appropriate safety countermeasures are already in force or are going to be taken with respect to the basic matters indispensable to the safe execution of tunnel construction.

For this purpose, a comprehensive check list was prepared, which includes more than 80 items as necessary requirements to ensure safe execution of tunnel work. Each item has a detailed guideline to help assess whether or not the corresponding safety measure in the execution plan is adequate. A study should also be made as to when and how the proposed safety measures are to be implemented. Table 6 illustrates a portion of the list items of basic matters with a detailed explanation for the assessment, in which work control organization requirements are presented. Many of these items listed as the basic matters, were selected from the articles related to tunnel construction work in the Safety and Health Law established in 1972, and other authorized engineering specifications.

Table 7 Potential risk evaluation of gas explosion

Element	Condition	Raw Score
Geology (G)	a. The tunnel is in an area with gas generation. The preliminary survey indicates that the geology has a possibility of great gas generation for the entire length.	3
	b. Part of the tunnel is either in or near an area of gas generation. The preliminary survey indicates that part of the geology involves an amount of gas generation.	2
	c. There is no gas generation	0
Length (L)	a. Long. (1,000m or more)	3
	b. Medium. (300m to less than 1,000m)	2
	c. Short. (less than 300m)	1
Cross section (A)	a. Small cross section (excavation cross section: less than $10m^2$). or uses a bottom heading and a sidewall heading.	3
	b. Medium cross section (excavation cross section : $10m^2$ to less than $50m^2$).	2
	c. Large cross section (excavation cross section: more than $50m^2$).	1
Type of tunnel approach (S)	a. Vertical shaft	3
	b. Inclined shaft	2
	c. Regular tunnel or adit.	1

R (risk for gas explosion) = $G \times (L+A+S)$

Table 8 Rank classification of potential risk of each anticipated accident

Rank	Gas explosion	Flooding	Fire	Transportation	Cave-in
I (High)	11 or more	13 or more	8 or more	8 or more	10 or more
II (Middle)	7–10	9–12	5–7	5–7	7–9
III (Low)	1– 6	1– 8	1–4	1–4	4–6
IV(Improbable)	0	0	—	—	—

Upon conducting the evaluation of the basic matters, corrective action including modification of the execution plan should be taken if necessary. These safety measure assessment tables for the basic matters prepared here is not only useful at the stage of work planning for assessment, but also can be effectively used as a check list during the execution stage as well.

3) Ranking of the potential risk of the anticipated accidents (3rd step)
After confirming the basic safety requirements for tunnel construction work in the preceding step, quantitative evaluation of the chances of occurrence of several serious accidents inherent to tunnelling work is achieved by taking the construction site's characteristics into consideration. Then in accordance with the scores obtained from numerical evaluation, assign the rank of degree of potential risk of the anticipated accidents to the specified construction site concerned.

Table 9 A portion of the list of items to be checked for each accident

Gas explosion	Excessive flooding	Fire	Transportation	Cave-in
(1) Preliminary survey 1) Boring survey 2) Collection of data 3) Survey tunnel	(1) Preliminary survey 1) Boring survey 2) Collection of data	(1) Fire control 1) Storage and handling of combustibles 2) Gas welding and cutting 3) Electric equipment 4) Smoking places, etc.	(1) Hauling methods	(1) Preliminary survey 1) Geological and other surveys 2) Collection of data
(2) Measurement of gas 1) Measuring instrument 2) Measuring method	(2) Excavation work 1) Horizontal boring 2) Drain tunnel 3) Concrete shot 4) Injection	(2) Making tunnel equipment	(2) Tunnel hauling equipment 1) Operation control regulations 2) provision of track bed 3) Inspection of signals and markings 4) Use of pushcars	(2) Excavation work 1) Excavating method 2) Check for loose stones 3) Arrangement of

Table 10 Safety measures against gas explosion

Item of study	Rank I	Rank II	Rank III
(1) Preliminary survey 1) Boring survey	Carry out a boring survey and measure the amount of gas inside the whole tunnel from the entrance. Analyze the boring core and make a precise survey on gas composition, content, etc.	Make a boring survey and measure the amount of gas. Also study and analyze the boring core.	Same as left.
2) Collection of data	Survey on generation of gas in past tunnel and under-ground works in the vicinity.	Same as left.	Same as left.
3) Survey tunnel	Excavate a survey tunnel, if necessary, and check for the output, pressure and composition of gas.	Study to excavate a test tunnel.	
(2) Measurement of gas 1) Measuring instruments	Use portable instrument for local measurement and stationary measuring instruments for permanent measurement where gas is likely to stagnate.	Provide portable measuring instruments.	Same as left.
	Set standards for the inspection and maintenance of measuring instruments.	Same as left.	Same as left.

From the result of accidents investigation in recent tunnelling work, it was recognized that major accidents that resulted in either many workers being injured or large amount of damage to work performance were identified as gas-explosion, fire, flood, cave-in, and accidents in transportation work. [2] In order to evaluate the potential risk of these anticipated serious accidents numerically for a specific tunnelling work, four primary elements of construction site' s condition were considered. Geological condition, length of tunnel, cross section of tunnel, and type of entrance approach, were employed for the analysis. To assess the conditions of the elements in conjunction with the potential risk of hazards, descriptive criteria about the conditions of elements and assigned raw scores were prepared for all anticipated accidents. Table 7 gives a detailed description of the element condition as well as the corresponding raw scores for the occurrence of gas explosion. The numerical potential risk assessment point could be analyzed by substituting the identified raw score into a pre-determined equation for each anticipated accident. This assessment point is then set into rank classification from I (high) to III (low) or IV (improbable). Table 8 illustrates the relation between rank classfication and assessment points for all anticipated accidents.

4) Check the safety measures against inherent accidents (4th step)
As the final stage of safety assessment, check to see if proper safety measures against anticipated inherent hazards are already undertaken in compliance with the grade of the potential risk which was evaluated in step 3.

Table 9 illustrates a portion of lists of necessary items to be checked for each inherent hazard. Table 10 demonstrates a portion of proposed safety measure guidelines to the items in accordance with the degree of potential risk, for gas explosion accidents. Similar tables of guidelines for other inherent accidents have also prepared. After thorough checking is accomplished, similar to step 2, additional necessary safety measures should be taken if the proposed safety measures in the execution planning are judged inadequate.

The Ministry of Labour has approved this assessment system and recommends to the contractors, who have full responsibility for the safety of workers, to employ it to evaluate the working schedule before they start the work.

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