Modeling and Simulation of sewer-job safety levels by system dynamics

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OBJECTIVE: *The objective of this study was to find the factors influencing sewer-job safety levels(AJSL), construct its safety input-safety levels SD flow chart, and set up its simulation model to forecast levels for operations in sewer preventing workers from casualties..*
METHODS: *By counting sewer-job accidents for recent 15 years in China, the factors influencing sewer-job safety levels were analyzed from the view of system engineering, the key factors, then, were obtained by analytic hierarchy process (AHP), at last by using system dynamics (SD), safety investment-safety level SD flow chart for sewer could be established, as well as AJSL could be predicted via Vensim simulation.*
RESULTS: *Sewer-job was a typical confine space work where accidents occur frequently due to limited working space and poor working conditions. Statistics showed that although advanced technology, including gas-monitoring, gas-control, sewer-design and sewer-auto-cleaning, was adopted to do jobs in sewer, risk in sewer-job in China has been being high as labor was needed in some particular jobs. By using AHP, we found that the key factors were human behavior and safety management, with a weight of 0.27 and 0.35. SD flow chart showed the dynamic relation between safety investment and safety level.*
CONCLUSION: *Key factors could be screen out via using AHP scored by experts; SD flow chart of sewer-job levels illustrated its dynamic relationship. Prediction model showed that both modeling and simulation appeared good to reveal safety levels of sewer-job.*
Keywords: *sewer-job, safety level, AHP, SD*

I. INTRODUCTION

Sewer-job was the job performed in sewer, including cleaning, dredging, and repairing sewage pipes. It was a typical confine space work where accidents occur frequently due to limited working space, poor working conditions, and toxic gases as there were kinds of trashes, leftovers and silts in sewer[1,2]. Reports about accidents in sewer were easily found worldwide some years ago[3,4], but little those years, except China. Although trucks for cleaning and dredging pipes and pumping silts[5], as well as facilities for monitoring toxic gas[6], had been used in sewer-job in China, casualties and accident incidence in sewer had been being high. Death Statistics[7], except injured workers, for poisoning accidents and suffocation accidents in sewer in China showed that, from 2000 to 2015, the incidence had been declined, but among all accidents, up to 26, with 92 dead, 9 accidents left 29 dead, contributed to wrong rescue operation.

Existing studies about sewer focused on the formation mechanism of poison gas[2], gas control technology[8,9] or monitoring technology[10], sewer design [11,12], or how to manage sewer[13]. Ridings[14] referred that legislation and plan activities were important to sewer-job, Kemper[15] saw the solution to the problem in three parts: legislation, enforcement and technology. If we knew the mechanism between sewer-job safety levels(AJSL) and legislation, enforcement, technology and other elements, it would pose a great help for us in enhancing safety levels in sewer. Since safety of sewer-job was complicated, with kinds of influencing factors including legislation, enforcement, technology, operator, and so on, finding them and explaining their relation, was crucial to prevent sewerage-workers from injury or harm. The aim of this study was to find these factors, determine their weight, construct the dynamic model of sewerage-job and simulate it.

II. SUBSYSTEMS AFFECTING SAFETY LEVEL OF SEWERAGE-JOB AND THEIR WEIGHTS

According to the basic theory and methodology of system engineering[16], the status of a system could be assessed from human, machine, materials, enforcement and environment. By the traits of sewer, the subsystems or factors of AJSL , then, could be identified as human's behaviour (HB), safety management (SM), environment (E), equipments and facilities (EF) and legal regulation (LR), referring to the study of Ji[17] and Wang[18]. Meanwhile, these five subsystems contained their own subsystems or factors, with dynamic relationship among them. So Analytic Hierarchy Process (AHP) [19] was used to determine the key factors among these five factors.

20 experts, including 10 sewer administrators and 10 staffs engaging in cleaning, dredging, and repairing sewer, were invited to give their points[20]. Judgment matrix of sewer-job safety levels counted according to experts' points was as shown in TABLE I. The weight of each subsystem was 0.27, 0.35, 0.11, 0.16 and 0.11, respectively. So the key factors were human's behavior and safety management.

TABLE I Judgment matrix of sewer-job safety levels and its processing

factors	HB	SM	E	EF	LR	M_i	$\overline{W_i}$	$\sum_{j=1}^{n}\overline{W_j}$	
HB	1	1/2	3	2	2	6	1.4309	0.27	$CR=\frac{CI}{RI}$ $=\frac{0.0389}{1.12}$ $=0.0347<0.10$
SM	2	1	3	2	2	24	1.8882	0.35	
E	1/3	1/3	1	1/2	1	1/18	0.5610	0.11	
EF	1/2	1/2	2	1	1	1/2	0.8706	0.16	
LR	1/2	1/2	1	1	1	1/4	0.5743	0.11	

III MODELLING OF SEWER-JOB SAFETY LEVELS BASED ON SYSTEM DYNAMICS

Since environment, equipments and facilities and legal regulation were not as important as human's behaviour, safety management, they were treated as a single factor without subsystems, so the effect of safety investment on them was not considered there. The casual loop diagram constructed using system dynamics for sewer-job was pictured in Figure 1.The feedback loops mainly were:

Safety investment↑→ psychological quality↑→ HB levels↑→ AJSL↑→ safety investment↓
Safety investment↑→ safety quality↑→ HB levels↑→ AJSL↑→ safety investment↓
Safety investment↑→ physiological quality↑→ HB levels↑→ AJSL↑→ safety investment↓
Safety investment↑→ self-management↑→ HB levels↑→ AJSL↑→ safety investment↓
Safety investment↑→ education level↑→ HB levels↑→ AJSL↑→ safety investment↓
Safety investment↑→ regulation of site work↑→ SM levels↑→ AJSL↑→ safety investment↓
Safety investment↑→ information management↑→ SM levels↑→ AJSL↑→ safety investment↓
Safety investment↑→ safety education and training↑→ SM levels↑→ AJSL↑→ safety investment↓
Safety investment↑→ organization management of site work↑→ AJSL↑→ AJSL↑→ safety investment↓

IV SIMULATION OF SEWER-JOB SAFETY LEVELS USING SIMULATION SOFTWARE VENSIM

Levels, rate and auxiliary variables of sewer-job system were shown in TABLE II. Simulation of sewer-job safety levels, pictured in Fig.2, was constructed based on rate variable fundamental in- tree modeling [21], using Vensim, according to system dynamic feedback principles. Combined with TABLE II and Fig.2, following equations, then, can be obtained:

Sewer-job safety level equation:

$$AQZSP=ZYL_1\times L_1(t).K+ZYL_2\times L_2(t).K//\text{auxiliary equation } (ZYL_1+ZYL_2=1) \quad (1)$$

Human's behaviour subsystem equations:

$$L_1(t).K= L_1(t).J+(DT)\times R_1(t) \quad (2)$$

$$R_1(t)=A_{11}\times ZYL_{1\text{-}1}+A_{12}\times ZYL_{1\text{-}2}+A_{13}\times ZYL_{1\text{-}3}+A_{14}\times ZYL_{1\text{-}4}+A_{15}\times ZYL_{1\text{-}5} \quad (3)$$

$$TR_1=ZTR\times BL_1 \quad (4)$$

$$A_{11}=TR_1(T)\times BL_{1\text{-}1}\times TR_1 \text{ to } A_{11}\times M_2 \text{ to } A_{11}\times M_1 \text{ to } A_{11} \quad (5)$$

$$A_{12}=TR_1(T)\times BL_{1\text{-}2}\times TR_1 \text{ to } A_{12}\times M_2 \text{ to } A_{12} \quad (6)$$

$$A_{13}=TR_1(T)\times BL_{1\text{-}3}\times TR_1 \text{ to } A_{13} \quad (7)$$

$$A_{14}=TR_1(T)\times BL_{1\text{-}4}\times TR_1 \text{ to } A_{14} \quad (8)$$

$$A_{15}=TR_1(T)\times BL_{1\text{-}5}\times TR_1 \text{ to } A_{15} \quad (9)$$

Safety management subsystem equations:

$$L_2(t).K= L_2(t).J+(DT)\times[R_2(t)+M_3\times M_3 \text{ to } L_2(t)] \quad (10)$$

$$R_2(t)=A_{21}\times ZYL_{2\text{-}1}+A_{22}\times ZYL_{2\text{-}2}+A_{23}\times ZYL_{2\text{-}3}+A_{24}\times ZYL_{2\text{-}4} \quad (11)$$

$$TR_2=ZTR\times BL_2 \quad (12)$$

$$A_{21}=TR_2(T)\times BL_{2\text{-}1}\times TR_2 \text{ to } A_{21}\times M_1 \text{ to } A_{21} \quad (13)$$

$$A_{22}=TR_2(T)\times BL_{2\text{-}2}\times TR_2 \text{ to } A_{22} \quad (14)$$

$$A_{23}=TR_2(T)\times BL_{2\text{-}3}\times TR_2 \text{ to } A_{23} \quad (15)$$

$$A_{24}=TR_2(T) \times BL_{2\text{-}4} \times TR_2 \text{ to } A_{24} \quad (16)$$

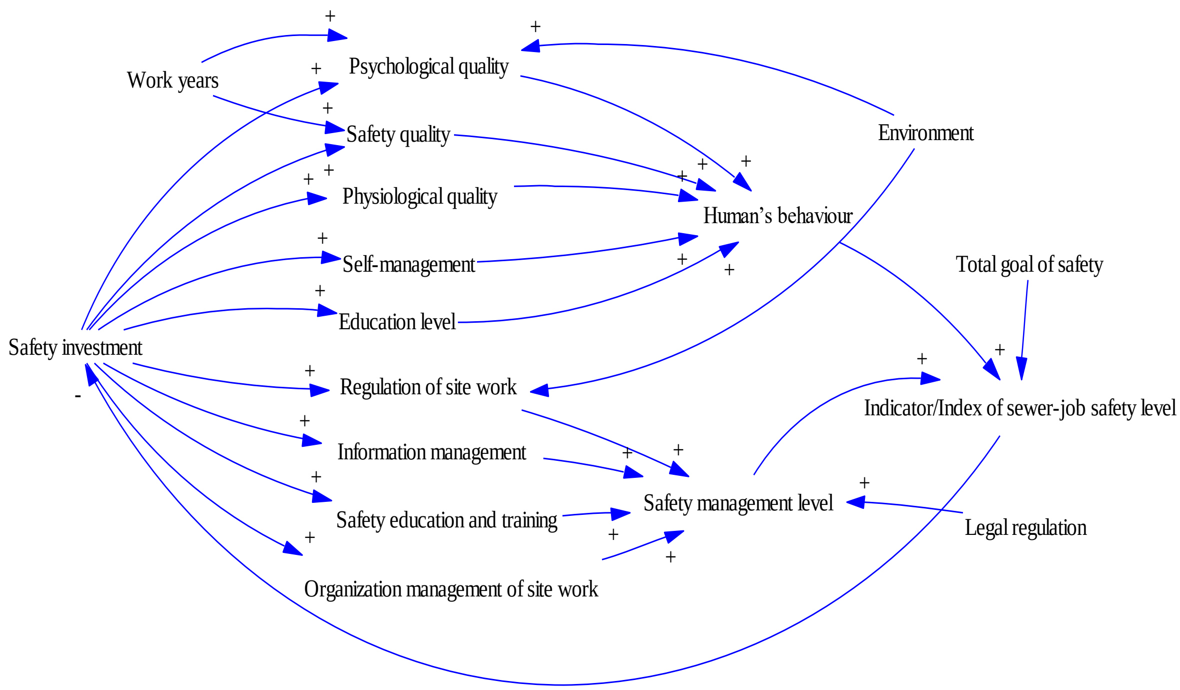

Fig.1 Casual loop diagram for safety investment and safety levels

Where, DT was time step, while other variables were initial values or constant values. Since assessing index for sewer-job safety levels were complicated, containing qualitative index and quantitative index, making it difficult to choose, safety-level assessing standard, referred to Wang[22], that were "excellent" (>90 points), "good"(80-89 points), "mean" (70-79 points), "barely passed" (60-69 points), "quite poor" (50-59 points) "poor" (40-49 points), "very poor"(<40 points), were established for sewer-job safety levels. Initial values, determined by variable assignment method, were substitute to Eq.(1) to Eq.(14), the development trend of sewer-job, then, could be obtained using Vensim PLE, pictured in Fig.4.

TABLE II Levels, rate and auxiliary variables of sewer-job system

Variables		Meaning
Level variables	$L_1(t)$	Safety level of human's behavior（Dimensionless Number）
	$L_2(t)$	Safety level of safety management（Dimensionless Number）
Rate variables	R_1	Level increment of human's behavior in unit time
	R_2	Level increment of safety management in unit time
Auxiliary variables	AQZSP	Indicator/Index of sewer-job safety level（Dimensionless Number）
	A_{11}	Index of level increment of psychological quality in unit time
	A_{12}	Index of level increment of safety quality in unit time
	A_{13}	Index of level increment of physiological quality in unit time
	A_{14}	Index of level increment of self-management in unit time
	A_{15}	Index of level increment of education level in unit time
	A_{21}	Index of level increment of regulation of site work in unit time
	A_{22}	Index of level increment of information management in unit time
	A_{23}	Index of level increment of safety education and training in unit time
	A_{24}	Index of level increment of organization management of site work in unit time
constants	ZTR	Total cost investing for human's behavior and safety management in unit time
	BL_1	Percentage of human's behavior investing (%)
	BL_2	Percentage of safety management investing (%)
	TR_1 to A_{11}	The rate of investment in psychological quality, increment of psychological quality generated by unit investment
	TR_1 to A_{12}	The rate of investment in safety quality, increment of safety quality generated by unit investment

	TR_1 to A_{13}	The rate of investment in physiological quality, increment of physiological quality generated by unit investment
	TR_1 to A_{14}	The rate of investment in self-management, increment of self-management generated by unit investment
	TR_1 to A_{15}	The rate of investment in education level, increment of education level generated by unit investment
	TR_2 to A_{21}	The rate of investment in regulation of site work, increment of regulation of site work generated by unit investment
	TR_2 to A_{22}	The rate of investment in information management, increment of information management generated by unit investment
	TR_2 to A_{23}	The rate of investment in safety education and training, increment of safety education and training generated by unit investment
	TR_2 to A_{24}	The rate of investment in organization management of site work, increment of organization management of site work generated by unit investment
	M_1 to A_{11}	The influence coefficient of environment on psychological quality, ranging from 0.5 to 1.5
	M_1 to A_{21}	The influence coefficient of environment on regulation of site work, ranging from 0.5 to 1.5
	M_2 to A_{12}	The influence coefficient of working years on safety quality, ranging from 0.5 to 1.5
	M_2 to A_{11}	The influence coefficient of working years on psychological quality, ranging from 0.5 to 1.5
	M_3 to $L_2(t)$	The influence coefficient of legal regulation on safety management, ranging from 0.5 to 1.5

As pictured in Fig.3, safety level of sewer-job came near the level of safety achievement after 35 months, the toll investment, then, could be decreased with a slower growth curve.

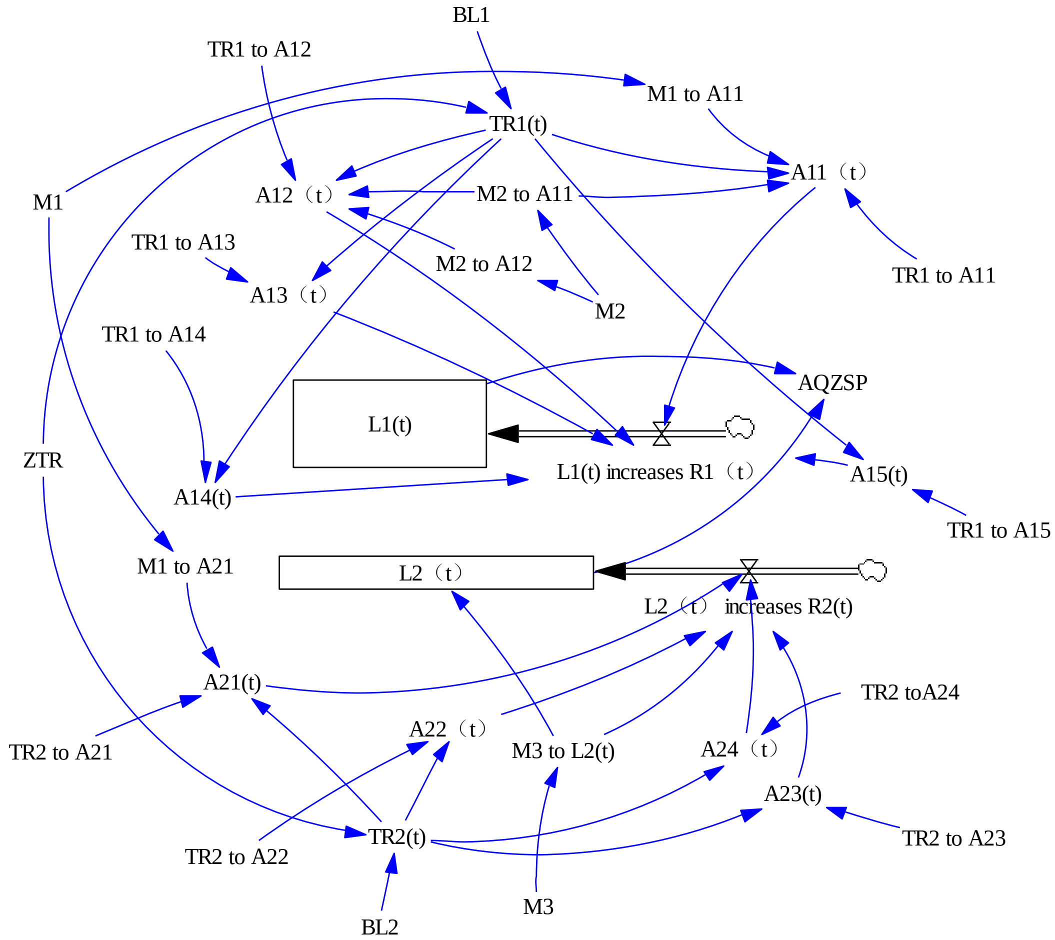

Fig.2 SD flowchart for safety investment-safety levels

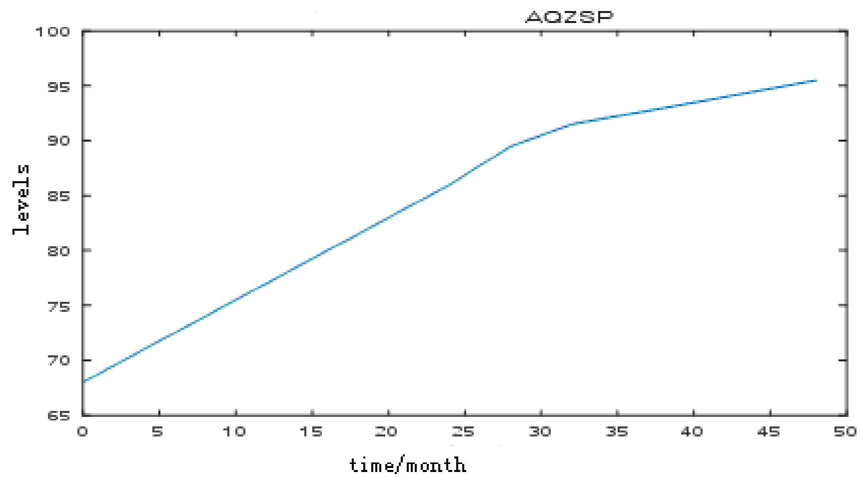

Fig.3 Development trend of safety levels

V CONCLUSION

Operation in sewer appeared to be simpler compared with works in other confine space work. This paper tried to find out the factors and key factors, leading to high risk work in sewer in China, by AHP, to determine their relation by SD, and to simulate the sewer-job safety levels with simulation software Vensim. It was conclude that the subsystems were human's behaviour, safety management, environment, equipments and facilities and legal regulation, and that the key factors were human's behaviour, safety management, with a weight of 0.27 and 0.35, respectively, calculated by AHP. Feedback loops for safety investment and safety levels of sewer-job, as well as their SD flow charts, were established based on system dynamics. Simulation results showed that safety levels of sewer-job reach the level of safety achievement after 35 months. The model and simulation method presented in this paper made it possible to supervise the sewer-jobs dynamically, help preventing and controlling accidents of sewer, as well as build preventive risk system.

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