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Coupling Analysis of Safety Influencing Factors in Subway Station Operation under a High-Pressure Gas Pipeline

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Abstract: A subway station's operation is susceptible to accidents when there is a high-pressure gas pipeline overlaying it, and analyzing the correlations between the safety influencing factors (SIFs) in this operating situation can provide paths to reduce safety accidents. Thus, this paper investigated the coupling correlations between the SIFs. We firstly identified the SIFs during subway station operation under a high-pressure pipeline (SSOUHP) based on a literature review and discussion with experts. Then, the analytic hierarchy process (AHP) and coupling degree analysis (CDA) were combined to assess the coupling correlations between the SIFs, and Y subway station was selected to test the proposed hybrid coupling analysis approach. Research results show that (a) 23 second-level SIFs were identified and these SIFs can be summed up into five first-level SIFs, namely, human-related SIFs, pipeline-related SIFs, station-related SIFs, environment-related SIFs, and management-related SIFs; (b) the proposed hybrid approach can be used to evaluate the coupling correlations between SIFs; (c) of the coupling situations during Y subway station's operation, the internal coupling correlations among environment-related SIFs, the coupling correlations between pipe-related SIFs and environment-related SIFs, and the coupling correlations among human-related SIFs, pipe-related SIFs, and environment-related SIFs are all greater than 1, and the coordination degree is 0.778, 0.781, and 0.783, respectively, which is a high security risk; (d) the overall coupling degree among all SIFs during Y subway station's operation is 0.995 and the coordination degree is 0.809, which is a low safety risk. The research can enrich knowledge in the safety evaluation area, and provide a reference for onsite safety management. The results are basically consistent with the conclusion of the enterprise report, which verifies the scientificity and validity of the evaluation method.

Keywords: subway stations; gas pipeline; influencing factors; coupling degree; coupling coordination degree

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1. Introduction

The national "14th Five-Year Plan" pointed out that it is necessary to build a multi-level rail transit network in urban agglomerations and metropolitan areas, promote the rail construction of key urban agglomerations, accelerate the construction of a multi-network integration system, and make overall use of existing lines and new lines [1]. By the end of 2022, there were 308 urban rail transit lines in 55 cities in China, with a total length of 10,287.45 km. Among them, the subway operating lines are 8008.17 km, accounting for 77.84%, and the length of the newly opened line is 1080.63 km [2]. With the development of the network, gas pipelines and subway stations are closely related in operation, and their spatial proximity, parallel, or intersection will inevitably form a new urban safety regional coupling risk [3,4]. Leakage or damage of gas pipelines may affect the normal operation of a subway line, and, more seriously, can cause an explosion or fire and threaten the personnel's safety in subway stations or their surrounding area [5]. Furthermore, the settlement [6], high-frequency vibration [7], and stray current [8] of subway stations during operation also can exert an impact on a gas pipeline, and lead to the rupture or damage of the gas pipeline, and thus, an accident caused by gas leakage occurs. In 2008, a gas leak occurred in Guangzhou Subway Line 6 due to improper construction of a gas pipeline, causing an explosion and killing seven people. In 2021, a gas pipeline was damaged by a construction unit, resulting in a gas pipeline leakage of about 10,000 m^3 of natural gas overlaying the subway stations of Hangzhou Line 9. These accidents not only brought about a large number of delays and casualties, but also spawned huge losses to the social economy.

Previous research has mainly concentrated on identifying SIFs and analyzing their coupling effects in subway systems. In terms of identification of SIFs, most scholars attribute the safety factors to four aspects: human, facilities and equipment, environment, and management [9–11]. In the analysis of the coupling of SIFs, scholars usually use the interpretive structure model [12], N-K model [13], coupling degree model [14], system dynamics model [15], SHEL model [16], and so on. For example, Yu et al. [13] used the N-K model to construct a coupled subway operational safety risk model, measured the risk coupling value under different coupling methods, and obtained the single-factor, two-factor, and multi-factor risk coupling probability and the risk coupling value for different coupling methods. In Wang et al. [16], based on the SHEL model and AHP method, an identification and evaluation method for human error SIFs in human, machine, and environment system is proposed to research the human error SIFs in subway station systems. However, few in-depth studies have been conducted on operational safety during SSOUHP. Therefore, it is necessary to distinguish the factors affecting the safety of SSOUHP, to find out the most unfavorable risk coupling situation between subway stations and gas pipelines, and to avoid the safety hazards of subway stations and gas pipelines in complex environment such as spatial proximity, parallelism, or intersection, so as to provide a scientific basis for the safe operation of subway stations. However, there is a dearth of studies that specialize in the operational safety issues related to subway stations and gas pipelines, especially under complex spatial configurations. How to identify the key influencing factors in this scenario? How to apply these key influencing factors to analyze this complex internal coupling relationship? These will be the focus of our research.

With the continuous development of urbanization, the underground environment of cities is complex and intricate. Gas pipelines and subway stations, as important infrastructure of cities, are closely related to people's normal production and life. Once a gas pipeline leaks and causes explosion accidents, the safety and operational stability of subway stations will be threatened. The coupled analysis of the SIFs of SSOUHP is of great significance for ensuring the safety of people's lives and smooth urban transportation. Therefore, this paper uses a literature analysis and expert discussion to distinguish the SIFs of SSOUHP. Moreover, the internal coupling relationship of the operational safety of subway stations is also quantitatively described using AHP and CDA. Finally, an engineering case is chosen to validate the proposed model. The coupled analysis of the SIFs carried out for this paper not only provides some enlightenment and reference for the research in related fields, but also helps the relevant departments to formulate management regulations to provide a basis for the safe operation of subway stations.

2. Literature Review

2.1. Study on the SIFs of High-Pressure Gas Pipelines

In research on the safety factors of high-pressure gas pipelines, scholars mainly summarized from the perspectives of human factors [17], vibration [18], corrosion [19,20], equipment and operation [21], design [22,23], and so on. For example, Wang [22] and Yang et al. [23] mainly consider the safety of high-pressure gas pipelines from four aspects: "third-party damage", "corrosion", "misoperation", and "design". Bai et al. [24] summarized the main SIFs of high-pressure gas pipeline safety from four aspects: "third-party interference", "environment", "misoperation", and "material defects". Zeng et al. [21] constructed an index system of SIFs of urban gas pipeline safety including 105 bottom factors from four aspects: "third party damage", "corrosion", "equipment and operation", and "intrinsic safety quality of pipeline". Some scholars have supplemented the identification of the factors affecting the safety of high-pressure gas pipelines. For example, a risk assessment method based on cloud reasoning was suggested by Guo et al. [25] and included a number of factors, including aging, third-party damage, biological erosion, factor misuse, corrosion damage, and design faults. Depending on the pipeline properties, Zhang et al. [26] adjusted the SIFs such as corrosion factors, manufacturing and construction defects, soil movement, misoperation, leakage influence coefficient, etc., which improved the applicability of each influencing factor to the pipeline.

2.2. Study on the SIFs of Subway Station Operation

According to the 4M1E theory, most scholars attribute the safety factors to four aspects: human, facilities and equipment, environment, and management [9–11]. On this basis, Liu et al. [27] introduced the concept of emergency management, and identified 18 secondary subway operational SIFs from five aspects. Starting from the five basic dimensions of the physical constituents of subway stations, Du et al. [28] established a system of indicators of SIFs with structure, equipment, management, human, and environment as the main body. Some scholars have further analyzed the 4M1E theory, dividing "human" into "passengers" and "employees", dividing "environment" into "internal environment" and "external environment", and dividing "management" into "rules and regulations" and "prevention system" [29]. In addition, some scholars have summarized the safety influences on the operation of subway stations from other aspects. For example, Bai et al. [30] established the index system of SIFs of subway operational safety from four aspects: "safety management", "organization management", "equipment management", and "environment". Xiao et al. [31] extracted the main factors influencing the operational safety of subway stations from the aspects of "passengers", "equipment and facilities", and "emergency response capability". Li et al. [32] identified the SIFs of subway stations from four aspects: "operation management", "equipment and facilities", "employees", and "external environment".

2.3. Study on the Coupling of SIFs between Gas Pipelines and Subway Stations

In terms of coupling study on SIFs of high-pressure gas pipelines, Yang et al. [33] established a calculation model of coupling degree based on coupling degree theory, and used AHP and the entropy weight method to quantitatively analyze the coupling degree between different levels of factors. In order to determine the probability and coupling value of various coupling modes, Fu et al. [34] analyzed the influence of multi-factor coupling on the possibility of urban gas pipeline failure from four aspects: human, machine, environment, and pipe, constructed an N-K model based on a complex network, and calculated the probability of occurrence of different coupling modes and the value of coupling. Based on the risk factors of human, pipeline, operation and maintenance, and environment, a comprehensive index system of SIFs was established by Wang [35]. The coupling mechanism of risk factors of gas pipeline networks was analyzed, and the safety assessment of urban gas pipeline networks considering the coupling of complex disaster-causing factors was studied.

In the study of coupled factors affecting the safety of subway stations, scholars consider the problems from four aspects: "personnel", "management", "equipment", and "environment". In order to calculate the likelihood of subway operation accidents and the coupling value under different coupling modes, the N-K model is used to study the degree of influence of each factor and its coupling mode on urban subway operation [36,37]. Huang et al. [38] introduced the influencing factor of "materials transported on the subway", analyzed the formation mechanism of the coupling risk based on the N-K model and the trigger concept, and quantitatively described the internal coupling relationship of subway safety. In Shi et al. [39], based on the traditional node-place theoretical model, the evaluation model was optimized by adding the "connection" evaluation dimension, and the safety of subway stations was also evaluated using the coupled coordination degree model, in addition, in order to compensate for the limitations of qualitative analysis methods and make research more objective, scientific, and operational. Drawing on coupling degree theory, some scholars have established a coupling degree calculation model and quantitatively analyzed the coupling degree between the factors [14].

2.4. Summary of the Current Status of Research

In the field of safety evaluation of subway stations and gas pipelines, there is a lack of specific research processes and methods on how to accurately identify the key SIFs of SSOUHP. Current research mainly focuses on unilateral safety evaluation, i.e., independent safety analysis for subway stations or gas pipelines, respectively. However, with the increasing complexity and interdependence of urban infrastructures, the interaction between subway stations and gas pipelines has gradually become a factor that cannot be ignored. Especially in the case of SSOUHP, the impact of this coupling relationship on overall safety is particularly important. In addition, most current studies have focused on the fire risks, structural safety, and evacuation of people in subway stations, as well as the risks of corrosion, leakage, and third-party damage to gas pipelines. However, these studies tend to ignore the interaction between subway stations and gas pipelines, such as fires or explosions in subway stations that may be triggered by gas leaks, and the impact of subway station construction on gas pipelines. Therefore, this paper will try to analyze the SIFs of SSOUHP and the coupling of its key SIFs to improve the safety management of the subway and gas industries.

3. Identification and Coupling Model of SIFs of SSOUHP

3.1. Identification of SIFs of SSOUHP

3.1.1. Preliminary Identification of Operational SIFs

Identifying reasonable SIFs can help us comprehensively understand the SIFs of SSOUHP, and thus develop scientific and reasonable management strategies and response plans. This paper combines the research results of Yao [10], Zeng et al. [21], Fu et al. [34], and Xu et al. [36], and introduces the influence factor of "pipeline" according to the suggestion of the expert group, and divides the safety influence factors of SSOUHP into five aspects: human, pipeline, station, environment, and management.

In order to make the identified SIFs more systematic, scientific, and comprehensive, the keywords "subway stations" and "gas pipeline" and "SIFs", "subway stations" and "gas pipeline" and "safety evaluation" were combined and searched in databases such as CNKI and Web of Science. The publication time of the literature was set to 2000–2024. By analyzing the titles, abstracts, and keywords in the literature, 51 academic journals and 17 dissertations were finally identified for the screening of security SIFs, and 22 high-frequency SIFs were initially obtained, as shown in Appendix A.

3.1.2. Optimization of Operational SIFs

Through the method of expert discussion, 15 experts from design, owner, and research organizations were invited on-site to evaluate the acquired initial factors. According to the results of the experts' discussion, among the 22 high-frequency SIFs initially obtained through the literature screening, the factors "pipeline characteristics" and "pipeline equipment condition" were stated to have a cross-cutting relationship, and it was recommended that the factor "pipeline equipment condition" be deleted. In response to the "station factor", the experts suggested adding the factor of "localized structural failure". The experts pointed out that in underground construction, the safety risks caused by changes in geological conditions should not be ignored. However, "subsurface environment" includes "geological conditions", so we retained "the surrounding environment" factor and eliminated the "geological conditions" factor. In view of the imperfection of "environmental factors", the experts suggested adding the two factors of "complex social environment" and "vehicle squeeze". In addition, since the experts proposed that the impact of "policy and legal protection" on the safety of SSOUHP is not applicable in this article, this factor is replaced with "regulatory protection". Finally, the five major factors of "human", "pipeline", "station", "environment", and "management" were determined as the first-level SIFs and 23 second-level SIFs, as shown in Table 1.

Table 1. SIFs.

First-Level SIFs	Second-Level SIFs	Interpretation
Human factors	Human destruction	Damage caused by third-party construction, terrorist attacks, etc.
	Design errors	The design rationality, material selection, safety factor design, and other potential errors caused by the experience and qualification of the designers of the special design scheme.
	Misoperation by employees	Daily operational errors in pipeline or station caused by employees' lack of concentration, misunderstanding, work pressure, etc.
	Staff quality and experience	Including staff mental health, basic quality, responsibility, experience of similar projects, and regular training sessions.
	Safety awareness	Daily operation and maintenance staff education, training, safety awareness, safety attitude, safety knowledge popularization, and so on.
Pipeline factors	Internal corrosion of pipeline	The interaction between the inner wall of the pipeline and the impurities contained in the transported gas causes an accidental explosion accident caused by gas leakage after pipeline corrosion.
	Pipeline characteristics	Mainly the thickness of the pipeline, material, the likelihood of gas leakage after destruction, etc.
	Pipeline manufacturing defects	Accidental explosion caused by gas leakage caused by pipeline damage, small cracks, wrinkle bending, welding defects, or insufficient strength.
	Service life	Mainly due to disrepair and fatigue damage appearing after a long time of use.
	Operating pressure fluctuation	When the pipeline pressure is high, it will aggravate an accidental explosion caused by gas.
Station factors	Operation vibration	Fatigue damage to gas pipelines caused by the continuous cyclic action of vibration generated in subway operation.
	Stray current	Subway operation has some current leakage to form stray currents, which can cause galvanic corrosion on the pipeline.
	Settlement and displacement	The effect on the overall system of settlement and displacement generated by the main structure of the subway station during the operational phase.
	Local structural failure	Impact on the overall system after failure of the main structure such as beams, slabs, and columns in the subway station due to abnormal factors.
Environmental factors	The surrounding environment	In underground engineering, the safety risks brought by changes in geological conditions cannot be ignored. Its complexity and diversity pose a potential threat to the safe operation of subway stations and high-pressure gas pipelines.
	Relative position	The clear distance between the bottom of the high-pressure gas pipeline and the roof of the subway station.
	Natural disasters	Mainly the impact of natural disasters such as earthquakes, high temperatures, rainstorms, floods, and soil settlement on high-pressure gas pipelines and subway stations.
	Vehicle squeeze	The gas pipeline is laid under the road, and the long-term extrusion of vehicles will aggravate the wear of the pipeline. When the pipeline reaches its limit, the pipeline damage will cause an accidental gas leakage.
	Complex social environment	Mainly refers to the public safety awareness of the social group, the popularization of safety knowledge, the ability to prevent security, and the ability to report problems in time.

Table 1. *Cont.*

First-Level SIFs	Second-Level SIFs	Interpretation
Management factors	Daily operation and maintenance management	Configuration, installation and maintenance of software and hardware for the entire system of gas pipelines and subway stations.
	Accident alarm system	Monitoring of the status of gas pipelines and subway stations, and whether problems can be alarmed in a timely manner, and information transmission and sharing.
	Safety management practice	Including the preparation of emergency plans, emergency equipment configuration, accident management, etc.
	Rules and regulations guarantee	Whether the safety regulations and responsibility system are sound, whether the safety responsibility system is clear, and the implementation and supervision of responsibilities.

3.2. Coupling Model of SIFs of SSOUHP

3.2.1. Coupling and Coupling Degree Theory

The idea of coupling first appeared in physics, and it is thought to be a phenomenon in which (two or more) systems or forms of motion interact, influence, or unite with each other [40]. Richard [41] first proposed the theoretical model of coupling coordination degree in 1990. Since the Chinese scholar Jinchuan Huang introduced the concept of system coupling into the study of the relationship between urbanization and ecological environment in 2003, the research in this field has shown multidimensional characteristics. Coupling has been used in more disciplines, including ecology [42], agriculture [43], economics [44], and logistics [45]. Cong [46] explained and corrected the problems such as generalized expression errors, confusion of different coupling degree models, errors in coupling degree value range, and errors of coupling stage division from the physical meaning of coupling degree and the relevant literature in recent years.

The degree of coupling is an indicator for evaluating the degree of interdependence between different parts of the system [47]. The level or degree reflects the correlation and comprehensive effects among different SIFs. A higher coupling degree indicates that benign resonance coupling between the SIFs is achieved, and the system will gradually reach a new state of order. On the contrary, when the coupling degree is low, the system or the internal elements of the system are in an unrelated state, and the system will develop in a disorderly manner. Furthermore, each of these factors needs to be managed and controlled appropriately to ensure that the SIFs reach a benign and orderly state.

According to the coupling classification and the selection of the SIFs of SSOUHP, the coupling of the SIFs of SSOUHP can be divided into single-factor coupling, two-factor coupling, and multi-factor coupling, as shown in Table 2.

3.2.2. Coupling Model

Firstly, 15 experts from design, owner, and scientific research units are invited. The judgment matrix is determined by the experts' pairwise comparison and evaluation of the relative importance between two factors, and the importance of each influencing factor is calculated. The higher the score, the more important the influencing factor, and the higher the weight. The obtained weight is used to calculate the comprehensive index. Finally, the efficacy value of the ordering degree of the SIFs on the system is obtained through a composite index. The specific steps are as follows:

Step 1: Build the hierarchical model

Depending on the situation, the SIFs can be categorized from top to bottom as follows: target, rule, and scheme levels, as shown in Figure 1.

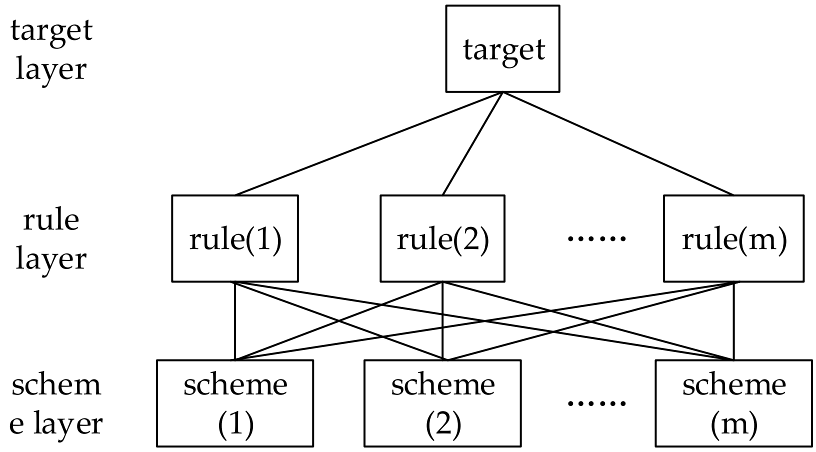

Figure 1. Hierarchy model diagram.

Table 2. Coupling of SIFs.

Single-Factor Coupling	**Two-Factor Coupling**	**Multi-Factor Coupling**		
		Three-Factor Coupling	**Four-Factor Coupling**	**Five-Factor Coupling**
Human–Human	Human–Pipeline	Human–Pipeline–Station	Human–Pipeline–Station–Environment	Human–Pipeline–Station–Environment–Management
	Human–Pipeline	Human–Pipeline–Environment		
Pipeline–Pipeline	Human–Environment	Human–Pipeline–Management	Human–Pipeline–Station–Management	
	Human–Management	Human–Station–Environment		
Station–Station	Pipeline–Station	Human–Station–Management	Human–Pipeline–Environment–Management	
	Pipeline–Environment	Human–Environment–Management		
Environment–Environment	Pipeline–Management	Pipeline–Station–Environment	Human–Station–Environment–Management	
	Station–Environment	Pipeline–Station–Management		
Management–Management	Station–Management	Pipeline–Environment–Management	Pipeline–Station–Environment–Management	
	Environment–Management	Station–Environment–Management		

Step 2: Build the pairwise comparison matrix

The first-level influencing factor is taken as the evaluation benchmark, and the pair comparison of the second-level influencing factor is carried out. The Satty 1–9 scale method [48] (as shown in Table 3) was used to assign values to each element.

Table 3. The meaning of scale method assignment.

Scale	Meaning
1	Both factors are equally important.
3	Factor i is slightly more important than factor j.
5	Factor i is more important than factor j.
7	Factor i is significantly more important than factor j.
9	Factor i is extremely important compared to factor j.
2, 4, 6, 8	Scale between two neighboring levels of importance.
Count backwards	The importance of factor i relative to j is a_{ij}, and the importance of j relative to i is $a_{ji} = 1/a_{ij}$.

The pairwise comparison matrix is as follows:

$$A_i = \begin{bmatrix} 1 & a_{12} & \ldots & a_{1j} & \cdots & a_{1m} \\ \frac{1}{a_{12}} & 1 & \ldots & a_{2j} & \ldots & a_{2m} \\ \vdots & \vdots & 1 & \vdots & \vdots & \vdots \\ \frac{1}{a_{1j}} & \frac{1}{a_{2j}} & \ldots & 1 & \ldots & a_{im} \\ \vdots & \vdots & \vdots & \vdots & 1 & \vdots \\ \frac{1}{a_{1m}} & \frac{1}{a_{2m}} & \ldots & \frac{1}{a_{ij}} & \ldots & 1 \end{bmatrix} \quad (1)$$

$$A_i a_{ji} = \frac{1}{a_{ij}} \quad (2)$$

where A_i is the pairwise comparison matrix of first-level SIFs; a_{ij} is the scale value of the *i* and *j* second-level SIFs.

Step 3: Consistency check

In the AHP, the subjective judgments and comparisons made by experts may involve certain subjective errors and biases. By using a consistency check, the credibility of the AHP can be enhanced. This ensures that the weight results are more reliable and accurate, thus improving the reliability of the decision-making process. When *CI* and *CR* are less than or equal to 0.1, the consistency check is passed.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

where *CI* is the consistency index; *n* is the order of pairwise comparison matrix.

$$CR = \frac{CI}{RI} \quad (4)$$

where *CR* is the ratio of consistency to the random consistency index; *RI* is the random consistency index, and its value is based on the research results of Zhang et al. [49], as shown in Table 4.

Table 4. RI Value.

Order	3	4	5	6	7	8
RI value	0.52	0.89	1.12	1.26	1.36	1.41

Step 4: Calculate the criterion weight vector

Because the weight is the evaluation given by the subjective judgment of the experts when comparing in pairs, there is a gap with the real value to some extent. Therefore, when

A is a consistent matrix, the maximum eigenvalue λ_{max} in the A matrix is used instead. The criterion weight vector can be calculated by the following formula:

$$(A_i - \lambda_{max})w_{ij} = 0 \tag{5}$$

where λ_{max} is the maximum eigenvalue of the paired comparison matrix; w_{ij} is the criterion weight vector of the j-th second-level SIFs under the i-th first-level SIF.

Step 5: Calculation of the comprehensive index of SIFs

The evaluation results of the first-level SIFs are transformed into the evaluation matrix A, and the comprehensive index of the influencing factor is calculated by the weight coefficient of the influencing factor of the middle level, which can be calculated by the following formula:

$$x_{ij} = \sum_{j=1}^{m} w_{ij}a_{ij} \tag{6}$$

where m is the number of second-level SIFs (the order of the matrix); x_{ij} is the comprehensive index of the j-th second-level SIF under the i-th first-level SIF.

Step 6: The construction of the power function

The following formula for calculating the ordered positive efficacy vector of the second-level SIFs to the first-level SIFs can be adopted:

$$u_{ij} = \frac{x_{ij} - \beta_{ij}}{\alpha_{ij} - \beta_{ij}} \tag{7}$$

The following calculation formula of the negative efficacy vector can be adopted:

$$u_{ij} = \frac{\alpha_{ij} - x_{ij}}{\alpha_{ij} - \beta_{ij}} \tag{8}$$

where α_{ij}, β_{ij} are the upper and lower limits of the comprehensive index of SIFs when the system is stable; u_{ij} is the satisfaction degree of each SIF to achieve the goal. The larger the value, the higher the satisfaction degree. The u_{ij} is [0,1].

The contribution of the order parameters of each second-level SIF to the order degree of the first-level SIFs can be calculated by using the line weighting sum method:

$$u_i = \sum_{j=1}^{m} w_i u_{ij} \tag{9}$$

where m is the number of second-level SIFs (order parameter); u_i is the efficacy value of the i-th second-SIF on the order degree of the first-SIFs.

Step 7: Coupling Degree and Coupling Coordination

The coupling function model is used to describe the interaction relationships between various parts of the system. The basic idea is to treat the various parts of the system as interrelated variables, and to describe their interactions by establishing mathematical relationships between them. Drawing on the concept of capacity coupling and the model of capacity coupling coefficients in physics, we generalize to obtain the multiple system (or element) interaction coupling degree model [50]. For example:

$$C = m * \sqrt[m]{\frac{\prod_{i=1}^{m} u_i}{\left(\sum_{i=1}^{m} u_i\right)^m}} \tag{10}$$

where C is the coupling degree of the system; m is the number of SIFs.

The coupling coordination model is a quantitative method used to evaluate the degree of coupling and coordination between different systems or factors. There are obvious differences and connections between coupling coordination degree and coupling degree [14]. It is difficult for the degree of coupling to reflect the “efficacy” and “synergy” of the SIFs, especially in the case of comparative studies of multiple factors. It may be misleading to use only coupling degree discrimination. The coupling coordination degree can make up for the disadvantages of the coupling degree. For this reason, coupled coordination needs to be introduced to account for the degree of synergy between the systems of SIFs.

The degree of coupled coordination evaluates the extent to which elements within a system or between systems interact with each other in the development process. It can show a tendency for the system's constituent components to move from disorder to order. Additionally, it is a quantitative index that measures the degree of coupling coordination. The level of coordination between the SIFs inside the system is worse when the coupling coordination degree is closer to 0. The level of coordination between the SIFs inside the system is better when the coupling coordination degree is closer to 1. Additionally, when the degree of coupling coordination is strong, it can effectively encourage the coordinated development of the subway station's safe operation. The criteria for classifying the coupling coordination degree refer to the existing research results [51,52], as shown in Table 5.

Table 5. Standard for classification of coupling coordination degree.

Coupling Coordination Degree Interval	Degree of Coordination	Coordinated Contrast Type
[0.0~0.1]	Dysfunctional recession	Extreme disorder
(0.1~0.2]		Severe disorder
(0.2~0.3]		Moderate disorder
(0.3~0.4]		Mild disorder
(0.4~0.5]	Transitional coordination	Critical coordination
(0.5~0.6]		Barely coordination
(0.6~0.7]		Junior coordination
(0.7~0.8]	Coordination development	Moderate coordination
(0.8~0.9]		Good coordination
(0.9~1.0]		High-quality coordination

The present study will utilize the research findings of Ji et al. [53] and Wang et al. [54] as references to establish a coupling coordination degree model and appraise the extent of interactive coupling coordination. The formula is as follows:

$$T = \sum_{i=1}^{m} b_i u_i \tag{11}$$

$$D = \sqrt{CT} \tag{12}$$

where T is the comprehensive harmonic index; b_i is the undetermined coefficient of the second-level SIFs, which is obtained by referring to the research results of Hou et al. [55], $b_1 = b_2 = \ldots b_m$, and $\sum_{i=1}^{m} b_i = 1$; D is the coupling coordination degree.

4. Case Study and Discussion

4.1. Case Background

The Y Station project of Line X in Zhengzhou is an underground three-layer, double-column, three-span, island-type station. The platform width is 14 m, and the station main body is 188.0 m long. The standard segment width is 23.15 m, and the expanded segment width is 23.65 to 29.65 m. The center mileage of the station is K11+900557. It is equipped with three sets of wind pavilions, one safety entrance, one transfer hall, one transfer passage, and one connecting passage. The project is located on the north side of the intersection of two main roads. The east–west and north–south roads are both eight lanes in two-way. The planned road width is 60 m. The road traffic is busy and the traffic flow is large. Due to the existence of water supply pipes, heat pipes, sewage pipes, power, communication, and other facilities near the roof of the station, the surrounding environment of the subway station is too complex to bypass the high-pressure gas pipeline.

Therefore, after the completion of the project, it is necessary to permanently relocate the high-pressure gas pipeline to a position lying above the station. In addition, the elevation of the bottom of the high-pressure gas pipeline is −1.962 m, while the elevation of the station roof is −3.254 m, which leads to a close distance between the high-pressure gas pipeline and the station roof, and there are certain safety hazards. Therefore, it is necessary to analyze the coupling factors influencing the safety of HPGPOSS.

4.2. The Construction of Hierarchy Model of SIFs in Case Study

The SIFs of the project have been identified throughout Section 3.1.1. Therefore, for the coupling analysis of the SIFs of this case, the optimized influencing factor in Section 3.1.2 can be directly applied to construct the hierarchical structure model figure shown in Figure 2.

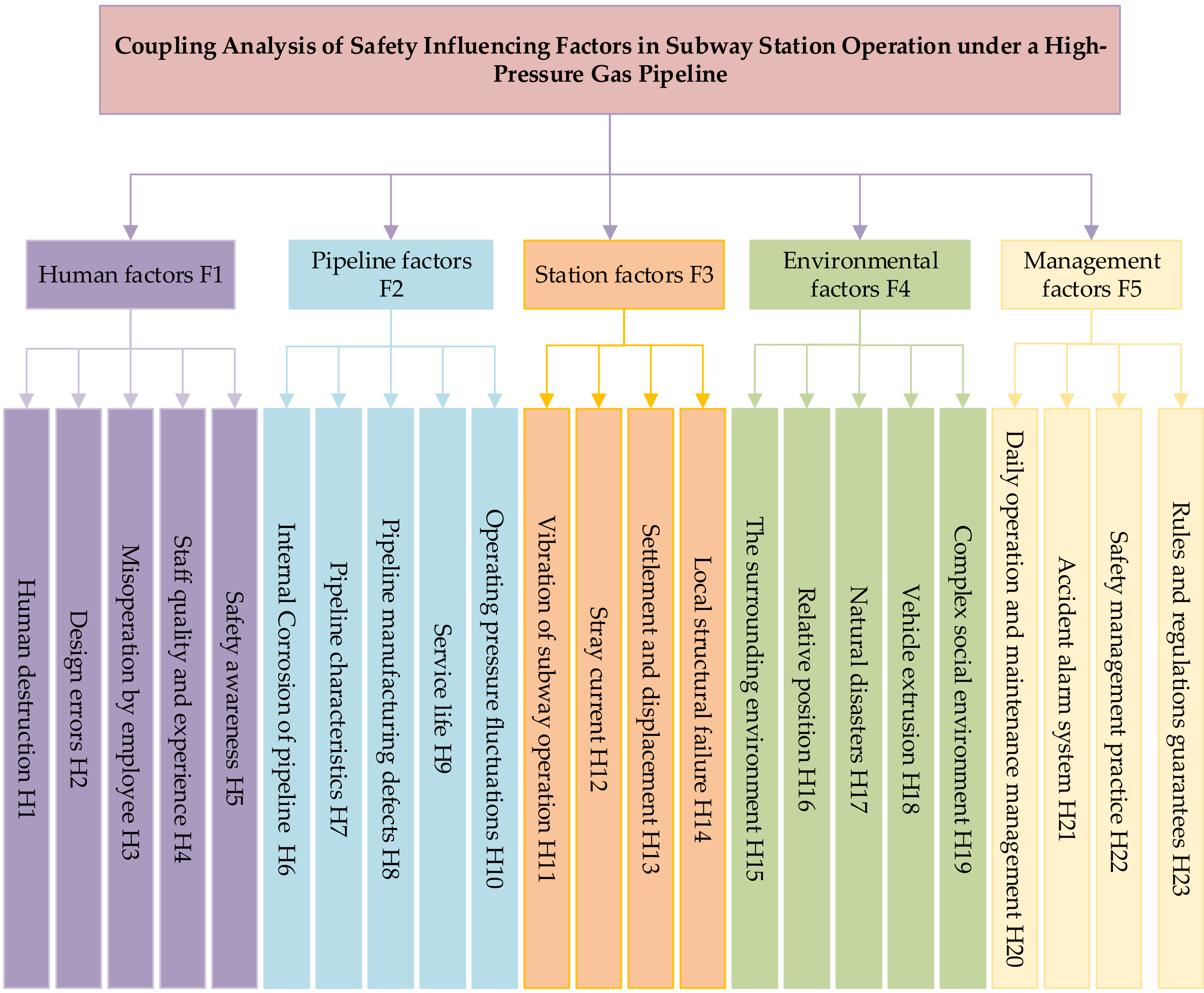

Figure 2. Hierarchy model of SIFs.

4.3. Case Calculation

Firstly, 15 experts in the field were invited to evaluate the scores of the second-level SIFs (1–9 points). Then, we take the average value as the initial value vector of each second-level SIF. Finally, the relative importance of the second-level SIFs (see Sections 3.1.1 and 3.1.2 for details) is compared to form a pairwise comparison matrix.

$$A_1 = \begin{bmatrix} 1 & 1 & 4 & 2 & \frac{1}{2} \\ 1 & 1 & 4 & 2 & \frac{1}{2} \\ \frac{1}{4} & \frac{1}{4} & 1 & \frac{1}{2} & \frac{1}{5} \\ \frac{1}{2} & \frac{1}{2} & 2 & 1 & \frac{1}{3} \\ 2 & 2 & 5 & 3 & 1 \end{bmatrix} A_2 = \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{2} & \frac{1}{4} & 2 \\ 2 & 1 & 1 & \frac{1}{2} & 4 \\ 2 & 1 & 1 & \frac{1}{2} & 4 \\ 4 & 2 & 2 & 1 & 5 \\ \frac{1}{2} & \frac{1}{4} & \frac{1}{4} & \frac{1}{5} & 1 \end{bmatrix} A_3 = \begin{bmatrix} 1 & 3 & \frac{1}{2} & \frac{1}{4} \\ \frac{1}{3} & 1 & \frac{1}{4} & \frac{1}{5} \\ 2 & 4 & 1 & \frac{1}{3} \\ 4 & 5 & 3 & 1 \end{bmatrix}$$

$$A_4 = \begin{bmatrix} 1 & \frac{1}{4} & \frac{1}{3} & 2 & \frac{1}{2} \\ 4 & 1 & 2 & 5 & 3 \\ 3 & \frac{1}{2} & 1 & 3 & 2 \\ \frac{1}{2} & \frac{1}{5} & \frac{1}{3} & 1 & \frac{1}{3} \\ 2 & \frac{1}{3} & \frac{1}{2} & 3 & 1 \end{bmatrix} A_5 = \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{4} & \frac{1}{4} \\ 2 & 1 & \frac{1}{3} & \frac{1}{3} \\ 4 & 3 & 1 & 1 \\ 4 & 3 & 1 & 1 \end{bmatrix}$$

The maximum eigenvalues of each pair of comparison matrix calculated by Matlab2018b software are as follows:

$$\lambda_{max1} = 5.0257, \lambda_{max2} = 5.0267, \lambda_{max3} = 4.0277, \lambda_{max4} = 5.0860, \lambda_{max5} = 4.0206.$$

The CI and CR values of each matrix calculated by Equations (3) and (4) are shown in Figure 3.

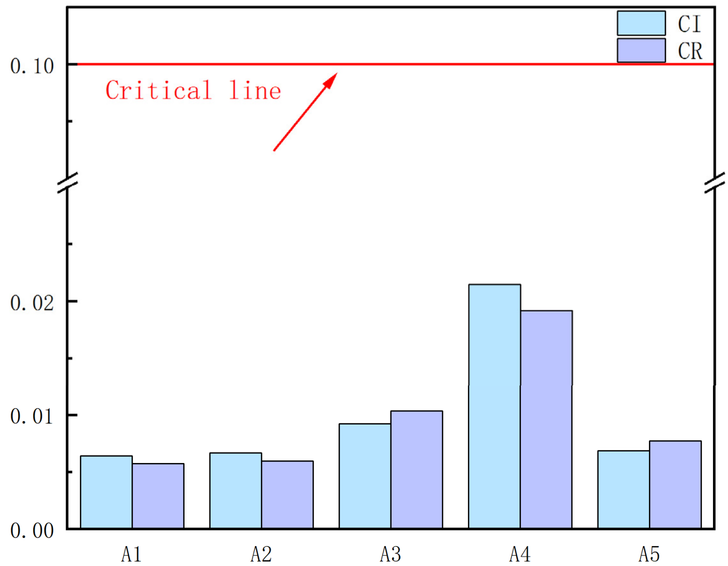

Figure 3. CI and CR values.

Both CI and CR are less than 0.1, and the consistency check meets the requirements.

Calculated by Formula (5) and corrected by Matlab2018b software, the weight values of each SIF are obtained, as shown in Figure 4.

According to Formula (6), the comprehensive index vectors of the SIFs are calculated as follows:

x_{1j} = (1.108, 1.108, 0.306, 0.586, 1.917)^{T} x_{2j} = (0.545, 1.090, 1.090, 1.999, 0.302)^{T}

x_{3j} = (0.615, 0.288, 1.001, 2.214)^{T} x_{4j} = (0.502, 2.139, 1.283, 0.338, 0.825)^{T}

x_{5j} = (0.351, 0.574, 1.548, 1.548)^{T}

The values of α_{ij} and β_{1j} are shown in Table 6.

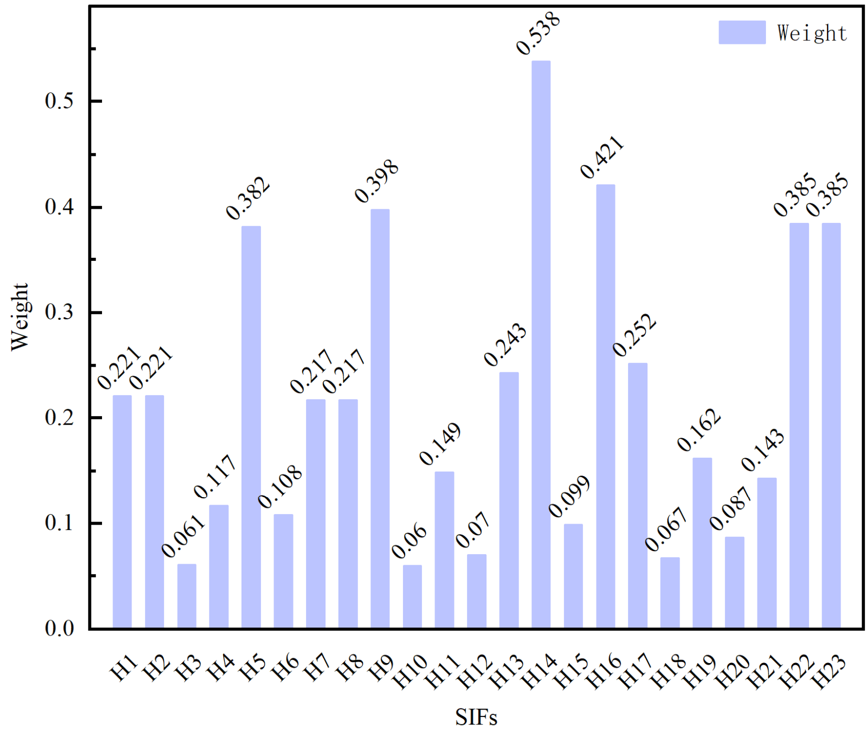

Figure 4. Weight value of each SIFs.

Table 6. Table of α_{ij} and β_{1j} values.

α_{ij}		β_{1j}	
α_{1j}	1.917	β_{1j}	0.306
α_{2j}	1.999	β_{2j}	0.302
α_{3j}	2.214	β_{3j}	0.288
α_{4j}	2.139	β_{4j}	0.338
α_{5j}	1.548	β_{5j}	0.351

The efficacy vectors of the SIFs are calculated by Formulas (7) and (8) as follows:
u_{1j} = (0.498, 0.498, 0.000, 0.174, 1.000)^T u_{2j} = (0.143, 0.464, 0.464, 1.000, 0.000)^T
u_{3j} = (0.170, 0.000, 0.370, 1.000)^T u_{4j} = (0.091, 1.000, 0.524, 0.000, 0.271)^T
u_{5j} = (0.000, 0.186, 1.000, 1.000)^T

The efficacy values of various SIFs on the system order degree are calculated using Formula (9) as shown in Table 7.

Table 7. Efficacy values of various SIFs on system order degree.

	U_1	U_2	U_3	U_4	U_5
Value	0.621	0.615	0.653	0.606	0.796

According to the coupling degree model, the coupling degree and coupling coordination degree among the SIFs are calculated by Formulas (10)–(12), and the results are shown in Table 8.

Table 8. Coupling degree and coupling coordination degree.

		Factors Set	T	D	Coupling Coordination Type
Single-factor		F1F1	1.000	0.788	moderate coordination
		F2F2	1.000	0.784	moderate coordination
		F3F3	1.000	0.808	good coordination
		F4F4	1.000	0.778	moderate coordination
		F5F5	1.000	0.892	good coordination
Two-factor		F1F2	1.000	0.786	moderate coordination
		F1F3	1.000	0.798	moderate coordination
		F1F4	1.000	0.783	moderate coordination
		F1F5	0.992	0.839	good coordination
		F2F3	1.000	0.796	moderate coordination
		F2F4	1.000	0.781	good coordination
		F2F5	0.992	0.836	moderate coordination
		F3F4	0.999	0.793	good coordination
		F3F5	0.995	0.849	moderate coordination
		F4F5	0.991	0.833	good coordination
Multi-factor	Three-factor	F1F2F3	1.000	0.793	moderate coordination
		F1F2F4	1.000	0.783	moderate coordination
		F1F2F5	0.993	0.820	good coordination
		F1F3F4	1.000	0.791	moderate coordination
		F1F3F5	0.994	0.828	good coordination
		F1F4F5	0.992	0.818	good coordination
		F2F3F4	0.999	0.790	moderate coordination
		F2F3F5	0.994	0.826	good coordination
		F2F4F5	0.992	0.816	good coordination
		F3F4F5	0.993	0.824	good coordination
	Four-factor	F1F2F3F4	1.000	0.790	moderate coordination
		F1F2F3F5	0.994	0.817	good coordination
		F1F2F4F5	0.993	0.809	good coordination
		F1F3F4F5	0.994	0.816	good coordination
		F2F3F4F5	0.994	0.814	good coordination
	Five-factor	F1F2F3F4F5	0.995	0.809	good coordination

The following conclusions are drawn from the analysis of the coupling degree and coupling coordination degree of each influencing factor.

(1) The analysis of the single-factor coupling results shows that the coupling degree of the internal SIFs is 1.000, indicating that the single-factor system is in a state of benign resonance coupling and orderly development. The order of coupling coordination degree of internal SIFs from large to small is management, station, human, pipeline, environment, and the coupling coordination degree of the internal SIFs of management and station is greater than 0.8. It shows that the coordination level between the internal factors of management and station is good, and they promote each other and develop coordinately;

(2) The analysis of the two-factor coupling results shows that the coupling degree between human and pipeline, human and station, human and environment, pipeline and station, pipeline and environment is 1.000, and the coupling degree between the other SIFs is greater than 0.9. It shows that the two-factor system is in a state of benign resonance coupling and orderly development. The order of coupling coordination degree of SIFs from large to small is station and management, human and management, pipeline and management, environment and management, human and station, pipeline and station, station and environment, human and pipeline, human and environment, pipeline and environment. Among them, the four types of two-factor coupling between station and management, human and management, pipeline and management, environment and

management are good coordination levels, and the remaining six types of two-factor coupling are moderate coordination levels;

(3) The analysis of multi-factor coupling results shows that the coupling degree of multi-factor coupling is greater than 0.9, indicating that the system is in a state of benign resonance coupling and orderly development under the action of multi-factor coupling. At the level of three-factor coupling, the factors of human–pipeline–station, human–station–environment, pipeline–station–environment, and human–pipeline–environment are coupled with each other to a moderate coordination level, and the remaining six types of three-factor coupling are coupled with each other to a good coordination level. At the level of four-factor coupling, the factors of human–pipeline–station–environment are coupled to each other at a moderate coordination level, and the remaining four-factor couplings are coupled to each other at a good coordination level. At the level of five-factor coupling, the coupling coordination degree is greater than 0.8, which indicates that the system of SSOUHP is at a good coordination level.

(4) By comparing the results of single-factor, two-factor, and multi-factor coupling, it can be found that with the coupling of environment, pipeline, and human the coupling coordination degree between the SIFs will decrease. It is noteworthy that the environmental factors have the strongest influence, followed by management factors, and finally human factors. As the station and management factors participate in the coupling, the coupling coordination degree between the SIFs will increase, and the management factors have the strongest influence. In addition, with the increase in the SIFs involved in coupling coordination, the coupling degree decreases. When the coupling degree is too high, it will affect the level of coupling coordination, and the frequency of coupling dispatch higher than 0.8 is increasing. When all the SIFs of the system participate in coupling, the coupling degree and coupling coordination degree are at a high level. Therefore, when analyzing the factors affecting the safety of SSOUHP, the more comprehensive the factors considered, the easier it is for the system to achieve benign resonance coupling, high-quality coordination, and orderly development.

Through the coupling analysis of the SIFs of SSOUHP, it is suggested that the relevant managers should control the interaction among the three key factors of environment, pipeline, and human factors, so as to avoid the coupling of unsafe influencing factors from the source of accidents. For example, (a) with regard to environmental factors, it is necessary to take into account not only the impact of the natural environment, but also the complex social environment, and to strengthen public safety education, the dissemination of safety knowledge, and public morality among members of social groups; (b) strengthening the management of human factors, reinforcing staff safety awareness, improving staff quality and experience; (c) focusing on the management of coupled risks, combining the influencing factors with the characteristics of the pipeline itself, so as to avoid accidents caused by pipeline failures. In addition, when managing the safe operation of subway stations, not only human factors, pipelines, and environmental factors are considered, but also some other factors. For example, (a) focus on the impact of subway operation vibration, stray current, settlement and displacement, and local structural failure on the safe operation of subway stations; (b) strengthening the daily operation and maintenance management of subway stations, regularly checking the accident alarm system, and improving safety and protection emergency measures and regulatory safeguards.

4.4. Discussion

This paper identifies 23 SIFs in five dimensions, human, pipeline, station, environment, and management, through literature research and expert discussion. In the existing research on the factors affecting the safety of subway stations, scholars have mainly considered the influence of "human", "mechanical equipment", "environment", "management", and other aspects [27,56,57]. Few people consider the impact of gas pipelines on the operational safety of subway stations. For example, Du et al. [28] considered the safety impacts of urban metro systems from a resilient city perspective from five perspectives: "structure", "equipment", "management", "human", and "environment", but again did not delve deeper into the impacts of pipeline safety. In view of this, this paper focuses on the special scenario of HPGPOSS, and focuses on the three dimensions of SIFs, namely, "human", "environment" (natural and social environment), "management", and "safety", through field research and an extensive literature review. We focus on the SIFs in the three dimensions of "human", "environment" (natural and social environment), and "management". The refinement of the classification of "environmental" factors not only matches the classification method adopted by previous scholars [58], but also reflects the comprehensiveness of the study. In order to be closer to the engineering reality, this paper innovatively adjusts "mechanical equipment and facilities" to a "station" factor, and classifies it as a first-level influence factor together with the "pipeline" factor. This adjustment is based on the physical composition of HPGPOSS [59], which makes the categorization of factors more scientific and systematic, and can reflect the actual situation more comprehensively.

In this paper, AHP is combined with a coupled coordination model to analyze the factors affecting the safety of the HPGPOSS. Based on the literature review, it is found that the commonly used coupling models are explanatory structure models, N-K model, coupling degree model, SD model, SHEL model, and so on, where interpretive structural models are suitable for analyzing systems with relatively complex relationships [60]. The N-K model is computationally demanding and labor-intensive in terms of the data used [61]. The SD model can only analyze and evaluate the coupling of two nonlinear systems, and the model requires a high sample size of data [15]. The elements in the SHEL model must be matched around people [62]. The coupling degree model is suitable for describing the coupling strength between systems or elements with coupling relationships, and it can realize quantitative evaluation of the coupling strength between elements with coupling relationships [14]. Compared with the high complexity of explanatory structural models, the resource-intensive nature of the N-K model, the two-system limitation of the SD model, and the human-centered nature of the SHEL model, the selected model is more intuitively able to show the interactions among the SIFs and the overall coordination status. Therefore, based on a comparison of commonly used coupling models in the literature, the coupling analysis model used in this paper makes it easier to analyze the magnitude of the coupling effects between the SIFs and the degree of mutual coordination.

In the comprehensive case analysis section, this paper systematically explores the intricate impacts of single-factor coupling, dual-factor coupling, and multi-factor coupling mechanisms on the safety of HPGPOSS. The core findings highlight that environmental factors, pipeline conditions, and human operations serve as the three pillars significantly influencing the system's safety performance. As these factors intertwine and couple, the coordination efficiency among SIFs within the system demonstrates a decreasing trend, reflecting the challenges posed by increased system complexity. It is noteworthy that current research in subway station safety widely acknowledges personnel, equipment, and the environment as the indispensable cornerstones of ensuring operational safety. Specifically, Yu et al. [13] emphasize the central role of personnel and equipment in subway operation safety; Xu et al. [36] further expand this perspective by including natural and management factors as key risk sources; while Zhao et al. [37], through detailed analysis, point out that the dominant SIFs shift from solely equipment and personnel to a multi-dimensional combination that includes management, particularly in multi-factor coupling scenarios. Particularly striking is the observation that as the number of SIFs participating in the coupling process increases, the system, despite facing rising coordination difficulties, gradually converges towards a stable and satisfactory level of coordination. This phenomenon is theoretically supported by the research of Xue Xiaofeng et al. [63], who note that while the coupling degree and coordination level among various influencing factors within subsystems exhibit significant numerical differences, the overall trend shows a decrease in coupling degree as the number of SIFs grows, ultimately reaching a dynamic equilibrium. This discovery profoundly reveals that the degree of coupling coordination among SIFs positively contributes to enhancing the resilience and recovery capabilities of subway station subsystems, particularly those in parallel with high-pressure gas pipelines [64].The empirical analysis of this paper also verifies this theoretical point of view, which provides an important reference and theoretical support for improving the safety management level of subway stations, especially in areas parallel to high-pressure gas pipelines.

The key SIFs we identified, combined with the proposed innovative hybrid method, and the profound results shown by the coupled model, not only open up new perspectives and insights for research in related fields, but also provide solid data support and scientific basis for related departments in formulating the management specifications for the safe operation of subway stations, which can help to further enhance the safety and efficiency of subway operations.

5. Conclusions

We identified the SIFs during SSOUHP based on a literature review and discussion with experts. A novel coupled analysis model of SIFs incorporating AHP and CDA is proposed, and a case study is used to demonstrate the feasibility of the proposed method. The results of the study are as follows:

(1) Aiming at the working conditions of SSOUHP, this paper summarizes 23 SIFs from five aspects, namely, human-related SIFs, pipeline-related SIFs, station-related SIFs, environment-related SIFs, and management-related SIFs, and constructs a hierarchical structure model of SIFs of SSOUHP;

(2) The AHP and CDA were combined to assess the coupling correlations between the SIFs, and Y subway station was selected to test that the proposed hybrid approach can be used to evaluate the coupling correlations between SIFs;

(3) In the coupling situations during Y subway station's operation, the internal coupling correlations among environment-related SIFs, the coupling correlations between pipe-related SIFs and environment-related SIFs, and the coupling correlations among human-related SIFs, pipe-related SIFs, and environment-related SIFs are all greater than 1, and the coordination degree is 0.778, 0.781, and 0.783, respectively. It is a high security risk. The overall coupling degree among all SIFs during Y subway station's operation is 0.995 and the coordination degree is 0.809, which is a low safety risk. The results are basically consistent with the conclusion of the enterprise report;

(4) In the future, we will improve the SIFs of SSOUHP, and we will conduct specific analysis on the relationship between coupling degree and coupling coordination among the influencing factors, as well as the causes and consequences of accidents. We hope to guide more readers to realize the importance of this research.

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Conflicts of Interest: Author Wenrong Yan was employed by the company Zhengzhou Metro Group Co. Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Initial Table of SIFs

First-Level SIFs	Second-Level SIFs	Source
Human factors	Human destruction	[25,65–67]
	Design errors	[25,65]
	Misoperation by employees	[23,25,65,66,68]
	Staff quality and experience	[10,58,65]
	Safety awareness	[10,58,69]
Pipeline factors	Internal corrosion of pipeline	[24,25,58,65]
	Pipeline characteristics	[25,65,70]
	Pipeline manufacturing defects	[25,58,65,67]
	Service life	[65]
	Operating pressure fluctuation	[25,65,70]
	Pipeline equipment condition	[58,65,71]
Station factors	Vibration of subway operation	[71,72]
	Stray current	[71,73,74]
	Settlement and displacement	[73]
Environmental factors	The surrounding environment	[58,75,76]
	Relative position	[70,73]
	Geological conditions	[72,75]
	Natural disasters	[23,66,67]
Management factors	Daily operation and maintenance management	[58,77,78]
	Accident alarm system	[65,75,79]
	Safety management practice	[10,58,75,79]
	Policy and legal protection	[10,58,65,75]

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