Diagnosing distresses of embankment dams using Bayesian network based on 150 incidents

Diagnostiquant les détresses des barrages de remblai utilisant le réseau Bayésien basé sur 150 incidents

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ABSTRACT
In recent years, dam safety draws increasing attention from the public. Diagnosis of dam distresses and corresponding causes is essential to ensure the safety of dams. To properly describe causes of dam distresses, it is necessary to study characteristics of the dams which have experienced certain incidents and shown signs of distress. In this work, a total of 150 incidents associated with 110 embankment dams in China are compiled into a database, including details of the dams, the distresses, and the causes. Based on the database, the distress characteristics of embankment dams are studied using the technique of Bayesian networks, which can tackle not only the multiplicity of dam distresses and causes but also the complex interrelations among the distresses and causes. The common patterns and causes of dam distresses are identified. In addition, a sensitivity analysis is conducted to find the most important factors contributing to the distresses of a dam. Such sensitivity analysis provides a solid basis for determining the priority of potential remedial measures. In the future, new dam incidents can be input into the Bayesian network for updating the diagnosing results.

RÉSUMÉ
Dans ce travail, un total de 150 incidents liés à 110 barrages de remblai en Chine sont compilés dans une base de données, y compris des détails des barrages, les détresses, et les causes. Basé sur la base de données, les détresse des barrages de remblai sont étudiées utilisant la technique des réseaux Bayésiens, qui peuvent aborder non seulement la multiplicité des détresses de barrage et des causes mais également les interdépendances complexes parmi les détresses et les causes. Les types et les causes des détresses de barrage sont identifiés. D'ailleurs, une analyse de sensibilité est conduite pour trouver que les facteurs les plus importants contribuant aux détresses d'un barrage. Une telle analyse de sensibilité constitue une base pleine pour déterminer la priorité des mesures curatives potentielles. À l'avenir, de nouveaux incidents de barrage peuvent être entrés dans le réseau Bayésien pour mettre à jour les résultats de diagnostic.

1 INTRODUCTION

Dams have been an essential part of critical infrastructures in society that contribute to social development and prosperity. On the other hand, many existing dams hold an increasing potential risk of failure due to structural deterioration, inadequate design, poor construction, and poor operations and maintenance. These dams are referred to as distressed dams. In China, the number of existing distressed dams is as large as approximately 37000 (Chen 2007). As social and economical development goes on, the potential risks posed by failures of distressed dams become more serious. Obviously, diagnosis of dam distresses and corresponding causes is essential to ensure the dam safety. Based on such understanding, appropriate remedial measures may be suggested for improving the safety of existing distressed dams.

Usually, the fault tree method is used to identify possible causes that contribute to a specific event and to build logical relationships among the elements of a system in the current practice of dam engineering (e.g. Hartford & Baecher 2004; Ma 2004; Fell et al. 2000). However, dam distresses and corresponding causes are often multiple and interrelated. Such a special feature requires a global consideration of a distressed dam by putting into perspective all the distresses and causes. A large fault tree can be difficult to understand. Therefore, the complex interrelationship of distresses and causes makes it extremely difficult to find the most important events. Another major disadvantage of the fault tree method is the difficulty of modelling the interactive influences among different distress mechanisms. Bayesian networks (Jensen 1996 & 2001) are preferable in the cases where dam distresses and causes are mutually dependent. The difficulties of the fault tree method in dam safety applications can be potentially overcome by applying the Bayesian network technique. For this reason, this paper uses the technique of Bayesian networks to study dam distress characteristics, which can tackle not only the multiplicity of dam distresses and causes but also the complex interrelations within them.

In this work, a total of 150 embankment dam incident cases that occurred in China are compiled into a database, including details of the dams, the distresses, and the causes. Based on the database, the distress characteristics of embankment dams are studied using Bayesian networks. The common patterns and causes of dam distresses are identified. In addition, a sensitivity analysis is conducted to find the most important factors contributing to the distresses of a dam, which provides a solid basis for determining the priority of potential remedial measures. In addition, Bayesian networks serve as a dynamic tool in the sense that new evidence may be inserted. In the future, new dam incidents can be inputted into the Bayesian network for updating the diagnosing results.

2 ESTABLISHMENT OF DATABASE

A total of 150 incidents associated with 110 embankment dams in China are compiled into a database. Details of the characteristics of the dams and the distress information are collected, including general information of the dams, the distresses, and the causes. This paper focuses on distresses of the embankment-foundation-abutment unit, whereas those of appurtenant structures (e.g. spillways, water-conveying tunnels, and gates) are not discussed. Most of the embankment dams were built during the 1950s-1970s, and are associated with poor design and construction due to limitations of knowledge and equipment of that time in China. Figure 1 compares the percentages of different

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Table 1. Categories of distress causes of embankment dams.

Distress pattern	Cause No.	Root cause
Foundation leakage/piping (FLP)	C1	Inadequate cutoff or filtered drainage at foundation (25 cases)
(40 cases)	C2	Incomplete sludge cleaning at foundation (15 cases)
Abutment leakage/piping (ALP)	C3	Fractures in abutment rocks or soils (4 cases)
(11 cases)	C4	Poor treatment of the embankment-abutment interface (7 cases)
Embankment leakage/piping (ELP)	C5	Burrows caused by termites (1 case)
(17 cases)	C6	Inadequate cutoff or filtered drainage inside embankment (5 cases)
	C7	Inappropriate or faulty embankment materials (8 cases)
	C8	Poor treatment of the fresh-old material bonding interface (3 cases)
Embankment cracking (EC)	C2	Uneven-settlement cracks (USC) caused by incomplete sludge cleaning at foundation (5 cases)
(40 cases)	C4	USC caused by poor treatment of the embankment-abutment interface (2 cases)
	C7	Freezing cracks (FC) caused by inappropriate or faulty embankment materials (2 cases)
	C7	Shrinkage cracks (SC) caused by inappropriate or faulty embankment materials (2 cases)
	C7	USC caused by inappropriate or faulty embankment materials (22 cases)
	C8	USC caused by poor treatment of the fresh-old material bonding interface (6 cases)
	C9	USC caused by poor installation of conduits through embankment (1 case)
Embankment sliding (ESLI)	C2	Incomplete sludge cleaning at foundation (3 cases)
(32 cases)	C6	Inadequate cutoff or filtered drainage inside embankment (4 cases)
	C7	Inappropriate or faulty embankment materials (11 cases)
	C8	Poor treatment of the fresh-old material bonding interface (2 cases)
	C10	Defective slope protection (2 cases)
	C11	Earthquake (5 cases)
	C12	Rapid drawdown of reservoir (1 case)
	C13	Steep slopes (4 cases)
Embankment slumping (ESLU)	C6	Inadequate cutoff or filtered drainage inside embankment (5 cases)
(10 cases)	C7	Inappropriate or faulty embankment materials (1 case)
	C9	Poor installation of conduits through embankment (2 cases)
	C10	Defective slope protection (2 cases)

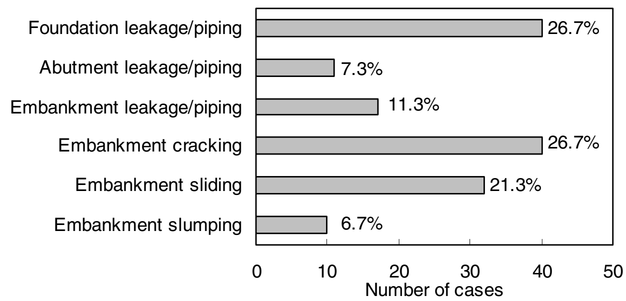

Figure 1. Percentages of distresses of embankment dams.

types of distresses of embankment dams. The root causes of dam distresses are summarized in Table 1.

It is found in Table 1 that the cause and distress relationships defining different distress mechanisms are strongly interrelated. These inter-relationships cannot be fully represented by the traditional fault tree method considering each mechanism independently. For instance, inappropriate or faulty embankment materials may cause embankment leakage/piping, cracking, sliding, and slumping.

Note that the database of distressed embankment dams established in this paper differs from an earlier dam-breach database (Zhang et al. 2009) that records the information of over 1600 dams already breached.

3 BAYESIAN NETWORKS

A Bayesian network is a directed acyclic graph formed by the variables (nodes) together with the directed edges, attached by tables of conditional probabilities of each variable on all its parents (Jensen 1996). Figure 2 shows a simple Bayesian network consisting of three variables X_1, X_2, and X_3. In this Bayesian network, the nodes without any arrows directed into them are called root nodes (X_1) and they have prior probability tables. The nodes that have arrows directed into them are called child nodes (X_2 and X_3) and the nodes that have arrows directed from them (X_1) are called parent nodes. Each child has a conditional probability table, given the state of the parent nodes. Note that the common parent X_1 introduces a dependency between X_2 and X_3. This is a typical situation in dam distress mechanisms, which has been mentioned in the former section.

Sensitivity analysis can be conducted in a Bayesian network to find the most important factors contributing to the distresses of a dam. It is achieved by simply altering the probability table of a selected node and checking the change in the probability table for the target node. For simplicity, each node in this study is assumed to have only two states, true (T) or false (F). Then, the importance of a node is represented by an index, I,

$$I = (P(TN) - P(TN|SN = F)) / P(TN) \quad (1)$$

in which P(TN) is the prior probability of the event represented by the target node, P(TN|SN = F) is the conditional probability of the event represented by the target node given nonoccurrence of the event represented by the selected node.

4 BAYESIAN NETWORK FOR DAM DISTRESSES

To develop a Bayesian network for diagnosing distresses of embankment dams, two issues are taken into account: 1) establishing the cause and distress relationships, and 2) determining the prior probability tables for root nodes and the conditional probability tables for other nodes. Based on the dam incident

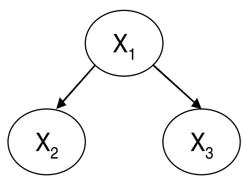

Figure 2. Illustration of a simple Bayesian network.

Table 2. Prior probability table for distress causes.

Cause No.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
P(Ci = T), i = 1-13	0.227	0.182	0.036	0.064	0.009	0.118	0.373	0.100	0.027	0.036	0.045	0.009	0.036

Table 3. Prior conditional probability table for the cause and distress relationships.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	USC
P(FLP)	1.000	0.750	-	-	-	-	-	-	-	-	-	-	-	-
P(ALP)	-	-	1.000	0.714	-	-	-	-	-	-	-	-	-	0.056
P(ELP)	-	-	-	-	1.000	0.385	0.146	0.273	-	-	-	-	-	0.056
P(ESLI)	-	0.150	-	-	-	0.308	0.244	0.182	-	0.500	1.000	1.000	1.000	0.028
P(ESLU)	-	-	-	-	-	0.385	0.024	-	0.667	0.500	-	-	-	-
P(USC)	-	0.250	-	0.286	-	-	0.537	0.545	0.333	-	-	-	-	-
P(SC)	-	-	-	-	-	-	0.049	-	-	-	-	-	-	-
P(FC)	-	-	-	-	-	-	0.049	-	-	-	-	-	-	-

Table 4. Comparison of calculated probabilities and historical frequencies of distresses.

Distress	FLP	ALP	ELP	EC	ESLI	ESLU
Calculated probability	0.333	0.095	0.143	0.312	0.256	0.088
Historical frequency	0.364	0.100	0.155	0.364	0.291	0.091

Table 5. Summary of the importance indexes of causes to corresponding distresses.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
FLP	0.589	0.318	-	-	-	-	-	-	-	-	-	-	-
ALP	-	-	0.358	0.463	-	-	-	-	-	-	-	-	-
ELP	-	-	-	-	0.056	0.287	0.399	0.175	-	-	-	-	-
EC	-	0.103	-	0.038	-	-	0.609	0.125	0.019	-	-	-	-
ESLI	-	0.086	-	-	-	0.109	0.305	0.059	-	0.055	0.137	0.027	0.109
ESLU	-	-	-	-	-	0.500	0.091	-	0.193	0.193	-	-	-

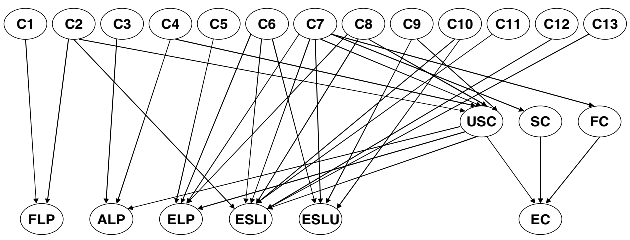

Figure 3. Bayesian network for diagnosing distresses of dams. Refer to Table 1 for the meanings of the symbols.

database, an inventory of possible dam distresses and corresponding causes is constructed. The mechanism of each distress and the diagnosis process are described as a set of causal chains that represent the cause and distress relationships. As a result, the Bayesian network considering all the distresses and corresponding causes involved is constructed in Fig. 3.

It is interesting to find out in Fig. 3 that the node of uneven-settlement cracks (USC) serves as not only a distress pattern but also a cause for other distresses. Uneven-settlement cracks may cause abutment leakage/piping, embankment leakage/piping, and embankment sliding. Among the 7 cases of poor treatment of the embankment-abutment interface (C4) leading to abutment leakage/piping (ALP), 5 cases have the processes of C4 causing ALP directly (C4-ALP) while 2 cases have the processes of C4 causing USC, which, in turn, causing ALP (C4-USC-ALP). In the database, the numbers of cases with other indirect processes of C7-USC-ELP and C7-USC-ESLI are 2 and 1, respectively.

As mentioned earlier, only two states (True/False) are considered for each node. For instance, "C1 = True" indicates that inadequate cutoff or filtered drainage at foundation does exist. Accordingly, P(C1 = T) represents the prior probability of inadequate cutoff or filtered drainage. In this paper, the prior probability table for distress causes and the prior conditional probability table for the cause and distress relationships are obtained based on results of the historical frequencies from the 150 incidents of the 110 distressed embankment dams (See Tables 2 & 3). For instance, the number of cases with inadequate cutoff or filtered drainage at foundation (C1) is 25, as shown in Table 1. Therefore, the prior probability of C1 is the number of cases with C1 divided by the total number of distressed dams, 25/110 = 0.227, as shown in Table 2. In other words, a distressed dam has a probability of 0.227 to involve inadequate cutoff or filtered drainage at foundation. It is also found in Table 1 that all these 25 cases with C1 involve foundation leakage or piping (FLP); hence the conditional probability of FLP given the occurrence of C1 is P(FLP|C1 = T) = 25/25 = 1.000, as shown at the intersection of P(FLP) and C1 in Table 3. Similarly, the prior probabilities of the other causes and the conditional probabilities of the other distresses given specific causes can be calculated and are summarized in Tables 2 and 3, respectively.

The calculation is conducted using program Hugin Lite developed by Hugin Expert A/S (2004). The program provides a tool for constructing a model-based decision support system using Bayesian networks. Based on the prior probabilities of the distress causes (C1-C13) in Table 2 and the conditional probabilities of the cause and distress relationships in Table 3, the probabilities of the distresses are obtained, as shown in Fig. 4. Table 4 shows that the calculated probabilities using Bayesian networks is almost the same as the historical frequencies based on the statistical analyses of the 150 incidents of the 110 distressed embankment dams. This proves the reasonability of using Bayesian networks for diagnosing dam distresses.

It is found in Table 4 that foundation leakage/piping (FLP), embankment cracking (EC), and embankment sliding (ESLI) are the three most important distress patterns. Both foundation leakage/piping and embankment cracking tend to occur during the early period of reservoir filling. Among the 27 cases of foundation leakage/piping with known incident time, 20 cases occurred within three years after the end of construction.

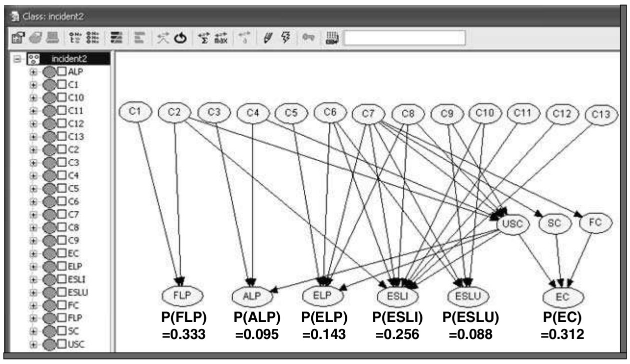

Figure 4. Probability calculation using program Hugin Lite.

Similarly, among the 30 cases of embankment cracking with known incident time, 18 cases occurred within three years after the end of construction. For embankment sliding, the loading conditions are as important as the embankment itself. In the database, 5 cases were caused by earthquakes while 1 case was caused by rapid drawdown of reservoir.

5 SENSITIVITY ANALYSIS

To find the most important cause of each specific type of distress, sensitivity analysis is conducted in the Bayesian network. Take foundation leakage/piping as an example. Assume the event of inadequate cutoff or filtered drainage at foundation (C1) does not occur, P(C1 = T) = 0 while P(C1 = F) = 1. Accordingly, the probability of foundation leakage/piping (FLP) in the Bayesian network is automatically updated, P(FLP|C1 = F) = 0.137. Similarly, P(FLP|C2 = F) = 0.227. It is known that P(FLP) = 0.333, and hence the importance indexes of C1 and C2 to FLP can be calculated using Eq. (1) as $I_{C1} = 0.589$ and $I_{C2} = 0.318$. Therefore, inadequate cutoff or filtered drainage at foundation (C1) is the most important cause of foundation leakage/piping (FLP). In the same way, sensitivity analyses are carried out in the Bayesian network for the other distresses, and the results of the importance indexes are summarized in Table 5. For instance, the value of 0.589 located at the intersection of FLP and C1 is the importance index of C1 to FLP.

Based on the importance indexes in Table 5, the most important cause for each specific distress is identified, which is the decision basis for the selection of optimal remedial measures. For foundation leakage/piping, inadequate cutoff or filtered drainage at foundation is the most critical cause, as mentioned before. Possible remedial measures include grouting, blanketing, new cutoffs, toe drains, pressure relief wells, and so on. For abutment leakage/piping, poor treatment of the embankment-abutment interface plays a leading role. This problem may be corrected by grouting through the interface. For embankment leakage/piping, inappropriate or faulty embankment materials is the most important cause. Excessive seepage through embankments, where permeability is relatively high or where leakage concentrates at anomalous regions, can be controlled by constructing an upstream seepage barrier, employing a slurry wall or membrane beneath the crest, and/or installing filtered drains on the downstream. Inappropriate or faulty embankment materials also contribute the most to embankment cracking and sliding. Most embankment cracking is referred to as the type of uneven-settlement crack. These cracks are often treated by excavating and backfilling, grouting, steel reinforcement, and so on. For embankment sliding, the weak soils in the sliding zone are always removed and replaced, sometimes accompanied by flattening slopes and/or lowering the phreatic surface via seepage cutoff and appropriate drainage. For embankment slumping, inadequate cutoff or filtered drainage inside embankment is found to be the key influencing factor. When slumps occur on the embankment surface, excavating and backfilling are usually adopted, which are followed by providing seepage cutoff and filtered drainage.

In general, the main distresses of an embankment dam and the corresponding causes are closely related to the seepage and slope stability. Therefore, the selection of remedial measures should be determined based on their influences on both the seepage stability and the slope stability. Extreme caution must be exercised to avoid sacrificing one aspect of stability while enhancing the other aspect of stability.

6 CONCLUSIONS

In this work, a total of 150 incidents associated with 110 embankment dams in China are compiled into a database. This paper then attempts to use a Bayesian-network technique to help diagnose the causes for dam distresses considering the multiplicity and complex interrelations of dam distresses and their corresponding causes. Several conclusions can be drawn:

1) Bayesian networks allow an effective global consideration of a distressed dam system by putting into perspective all of its components. The diagnosing results agree well with the historical frequencies, which shows that the preliminary outcomes of dam distress diagnosis using Bayesian networks are reasonable.
2) The sensitivity analysis in the Bayesian network allows the identification of the most important causes contributing to a specific distress, which provides a solid basis for determining the priority of potential remedial measures.
3) Foundation leakage/piping, embankment cracking, and embankment sliding are found to be the three most important patterns of embankment dam distresses. The corresponding most important causes for the above three distresses are inadequate cutoff or filtered drainage at the foundation, inappropriate or faulty embankment materials, and again inappropriate or faulty embankment material.

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