2128

RISK MANAGEMENT AND LIFELINE ENGINEERING

Shahinaz A BAKIR[1], David G ELMS[2] And John LAMB[3]

SUMMARY

One of the central problems in lifeline engineering is to achieve an integrated and balanced system so that for the most important elements of the lifeline the risk is evenly distributed and no part is more vulnerable than another. The paper demonstrates how a risk balancing technique can be applied by decision-makers to produce a guide as to how best to prioritise spending. A scenario is assumed in which a local authority decision-maker has a fixed budget to be spent among different possible modes of expenditure. The theory is given as to how this should be done to achieve the lowest overall risk. Failure can take place in different ways, each with an associated probability and consequence. An example is given of the application of the theory to expenditure on improvements to the seismic behaviour of the water supply lifeline in part of Christchurch, New Zealand.

INTRODUCTION

Lifelines and Their Risks

The study of the proper performance and maintainability of lifelines against various hazards is essential for the sustainability and safety of human civilisation and environment, quality of life and vitality of economic activities. Lifelines are water supply, sanitary and stormwater disposal, gas supply, electricity supply, telecommunications, broadcasting networks, transportation systems and building services (CAE 1991). Lifeline systems are generally considered to be an integral part of a community's infrastructure network. They provide the means of and conveyance for daily and critical services and products. Any lifeline failure can result in severe loss of functionality to the community and major damage to the environment. However, lifelines and their importance to our way of life generally are not recognised until their failure causes death and destruction, impedes emergency response following a major disaster, hinders post-disaster recovery, or paralyses an impaired community. Because lifelines are large and complex systems, they are susceptible to a wide range of natural and man-made hazards such as earthquakes, volcanos, flooding, tsunami, severe windstorm, severe snowstorm, slope hazard and accidents (CAE 1997). Therefore, their design and management requires a broad systems approach. It is essential to study the safety and reliability of lifelines under different imposed risks, in order to manage risks for reliable performance with minimum economic impacts pre- and post-disaster.

Seismic Risks of Lifelines

Lifeline systems are vulnerable to natural hazards, particularly to seismic effects. Because lifelines possess special characteristics, both in terms of physical construction and operation, they are in many ways more vulnerable than buildings or other single-site facilities. Some of the features that make lifelines unique were studied in a post Northridge earthquake workshop (NIST 1994)

The fact that many lifelines exist below ground imposes several unique problems for earthquake hazards. It is difficult to immediately detect damage that has occurred underground. Systems that utilise pipelines under pressure, such as water and gas supply, are more likely to quickly exhibit signs of damage or impact. The 1994 Northridge earthquake resulted in the most extensive damage to the U.S. water supply since the 1906 San

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[1] *Graduate Student, Department of Civil Engineering, University of Canterbury. e-mail : sab77@cad.canterbury.ac.nz*
[2] *Professor of Civil Engineering, University of Canterbury. e-mail: d.elms@civil.canterbury.ac.nz*
[3] *Project Manager, Christchurch Engineering Lifeline. e-mail: John.Lamb@extra.co.nz*

Francisco earthquake (NIST 1995). On the other hand, some post-earthquake damage to sewer systems, which are not generally pressurised, is very difficult to detect.

The post-earthquake performance of lifelines is usually measured by degree of outage or serviceability, but this does not take into account differential costs. Lifelines are required to provide important services after major hazards. To illustrate this importance, water supply is critical to fight post-earthquake fires, transport routes are essential for emergency vehicles, electric power service is necessary to ensure the continued operation of critical and essential facilities, and communication systems are essential in coordinating post-earthquake response and recovery efforts. Therefore, the proper design and management of lifeline facilities must consider acceptable and appropriate post-hazard performance criteria.

Risk Management of Lifelines

"Risk management is about living comfortably with risk. Its task is to control risk, not eliminate it" (Elms 1997B). Management is a matter of trying to produce a gradual improvement and of making sure there is no sudden degradation, while trying to balance cost against benefit (Palisade Corporation 1995, Scarff et al 1993). The goals of risk management are (1) to understand the risk and make sure that the unexpected could not happen, (2) to limit and control the extent of risk within an acceptable range, and (3) to balance and optimise the risk for the best possible outcome.

The essential problem is one of the optimum allocation of resources so that the lifeline operators, especially the community as a whole, can obtain the best performance and the lowest risk for a given investment. The point is to avoid sub-optimal solutions where each responsible group does what is best for them, and instead to have a coordinated overview to achieve the best overall results for the community. The application of proper risk management techniques for different natural and man-made hazards can provide good control on risks that resolves many performance and economic problems. Few studies of lifeline risks to date employ formal risk management techniques. The study described in the paper addresses risk management for lifelines using risk-balancing techniques developed at the University of Canterbury (Elms 1997A). The method identifies probable hazards and lifeline vulnerability, and provides a straightforward means of mitigating and controlling risks as well as giving quantitative guidelines for decision-makers. The approach is illustrated by applying it to the earthquake hazards of Christchurch City lifelines as a specific case study.

The objective of the study is to provide a systematic approach that supplies a step-by-step risk management process that can be applied to existing and new lifelines and incorporates risk balancing as guideline. The risk balancing method was presented initially by Elms (1979). The model was developed further in a later paper (Elms 1997A). Risk balancing is a useful tool for indicating which mitigation measure has the best effect on risk reduction and how much of each measure should be used in a limited resources situation. Although the method simple, yet it provides good insights. Risk balancing provides a quantitative method of distributing limited resources over the mitigated lifelines in order to achieve the minimal overall risk. Though the present paper applies the technique to lifelines in Christchurch, the method is general and can be used in a broad range of contexts.

RISK BALANCING

According to Elms (1997A), the risk-balancing technique was developed to optimise the expenditure on upgrades with a limited amount of money. This technique assumes a constant amount C that can be distributed among m expenditure modes according to their relative effect on the overall optimum upgrade. These different modes of expenditure a_j are defined as:

$$\sum_{j=1}^{m} a_j = C \qquad \textbf{(1)}$$

If there are n modes of failure, will be n cost consequences c_i. Each ci corresponds to failure mode i. Hence the total cost due to the n modes of failures F can be defined as:

$$F = \sum_{i=1}^{n} c_i p_i == \sum_{i=1}^{n} c_i \left(a_1, ..., a_m\right) p_i \left(a_1, ..., a_m\right) \qquad \textbf{(2)}$$

Where pi is the probability of failure corresponding to failure mode i.

In order to minimise the total failure consequence cost F, a Lagrange multiplier minimisation constraint can be applied as follows:

$$G = \sum_{i=1}^{n} c_i p_i - \lambda \left[\sum_{j=1}^{m} a_j - C \right] \qquad \textbf{(3)}$$

To obtain an optimum, the first partial derivatives with respect to a_j should come to 0; that is

$$\frac{\partial G}{\partial a_j} = \sum_{i=1}^{n} \left(\frac{\partial c_i}{\partial a_j} \right) p_i + \sum_{i=1}^{n} c_i \left(\frac{\partial p_i}{\partial a_j} \right) - \lambda = 0 \qquad (j = 1,\dots, m) \qquad \textbf{(4)}$$

The essence of the approach is to try to formulate the probability and consequence reduction in terms of easily understood variables. Assume that the cost consequences and the probability of failure are reduced in regards to expenditure a_j. There are basically three forms of reduction: (1) exponential reduction, (2) inverse power law reduction and, (3) curtailed power law reduction.

Assuming an exponential reduction for probability of failure in mode i gives:

$$p_i(a_1,\dots, a_m) = p_i^0 \left[1 - \sum_{j=1}^{m} r_{ij} \left(1 - \exp\left(-a_j / u_{ij} \right) \right) \right] \qquad \textbf{(5)}$$

Figure 1 illustrates the meaning of the constants $\mathbf{p_i^0}$, $\mathbf{r_{ij}}$ and $\mathbf{u_{ij}}$. The factor $\mathbf{r_{ij}}$ is the amount by which the initial failure probability can be reduced with unlimited expenditure. The standard reduction expenditure u_{ij} controls the speed at which an expenditure will begin to reduce the probability of failure. It is defined as the expenditure in mode j that will reduce the probability of failure in mode i by about 2/3 of the possible reduction in that mode.

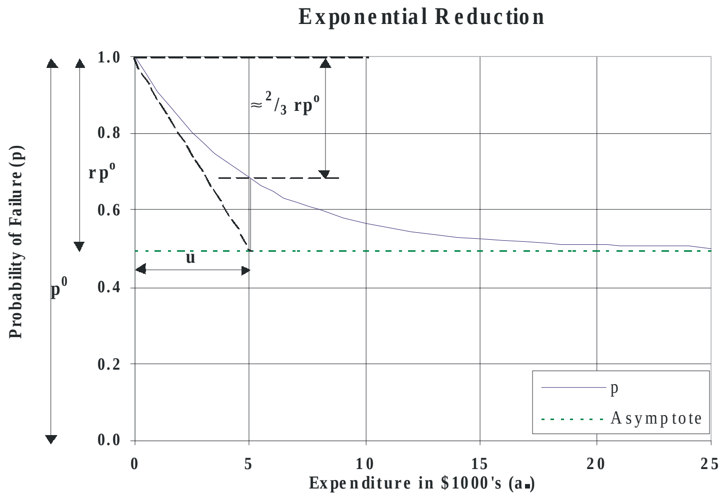

Figure 1 Reduction for Probability of Failure

Equation (4) can be expressed in analytical form by expanding the derivatives. In general the resulting expression will be non-linear. For ease of solution the function can be linearised using a first-order Taylor's series approximation about an assumed set of expenditures aj^0 to give:

$$\sum_{i=1}^{n} \left(A_{ij} + B_{ij} a_j \right) = \lambda \qquad (\mathrm{j} = 1 \dots \mathrm{m}) \qquad \textbf{(6)}$$

Where $$A_{ij} = F_{ij}^{0} - a_{j}^{0} f_{ij}^{0} \qquad (7)$$

$$B_{ij} = f_{ij}^{0} \qquad (8)$$

F_{ij}^{0} is the value of the function at the linearisation point a_j^0, f_{ij}^{0} is the derivative at the linearisation point, A_{ij} and B_{ij} are the 1st and 2nd coefficients of Taylor's linearisation respectively, and $a_j^0$is the initial assumed amount spent in expenditure mode j**.** This leads to an iterative solution for a_j and λ**.** **A** detailed description is given in Elms (1997A)**.** From equation (6) the expenditure cost a_j will be :

$$a_j = \frac{\lambda - \sum_{i=1}^{n} A_{ij}}{\sum_{i=1}^{n} B_{ij}} \qquad (9)$$

And, from the constraint of equation (1), the Lagrange multiplier is :

$$\lambda = \frac{C + \sum_{j=1}^{m} \left[\sum_{i=1}^{n} A_{ij} \Big/ \sum_{i=1}^{n} B_{ij} \right]}{\sum_{j=1}^{m} \left[1 \Big/ \left[\sum_{i=1}^{n} B_{ij} \right] \right]} \qquad (10)$$

Equation (9) gives the required explicit expression for optimal investment levels. Once the various parameters have been obtained it is a simple matter to compute the results by putting the parameters on a spreadsheet and iterating on the assumed values of expenditure.

CASE STUDY OF CHRISTCHURCH CITY

The city of Christchurch has complex systems of lifelines that include water supply, sanitary and stormwater disposal, gas supply, electricity supply, telecommunications, broadcasting networks, transportation systems and building services (CAE 1997). These lifelines are under the authority of different bodies and have different characteristics and interdependence (CAE 1997, 1991) that make their risk management difficult.

The case study deals with water supply failure as a result of an earthquake. The failure includes the failure of each of the elements in the pipework and pumping station (operational and/or structural failure). The example below applies the risk balancing procedure to estimate the optimal expenditure to minimise the cost of the failure in the pump stations in general.

As the work is at an early stage, the figures given are indicative only.

Water supply system

Christchurch is situated partly on a flat alluvial plain and partly on the Port Hills to the south. The City is bounded in the east by the Pacific Ocean and is underlain by aquifers. Christchurch water depends on rain and snow which falls on the Southern Alps and flows into rivers. Some water enters shingle riverbeds and flows into aquifers beneath the City. The City draws water from these aquifers (25-200 meters deep) and pumps it directly into the water supply system. Detailed information may be found elsewhere (CAE 1997).

Fault Tree

The fault tree shown in Figure 2 gives the interrelationship between different failures and their impact on failure of the overall system. The details were obtained from the Christchurch City Council Water Unit.

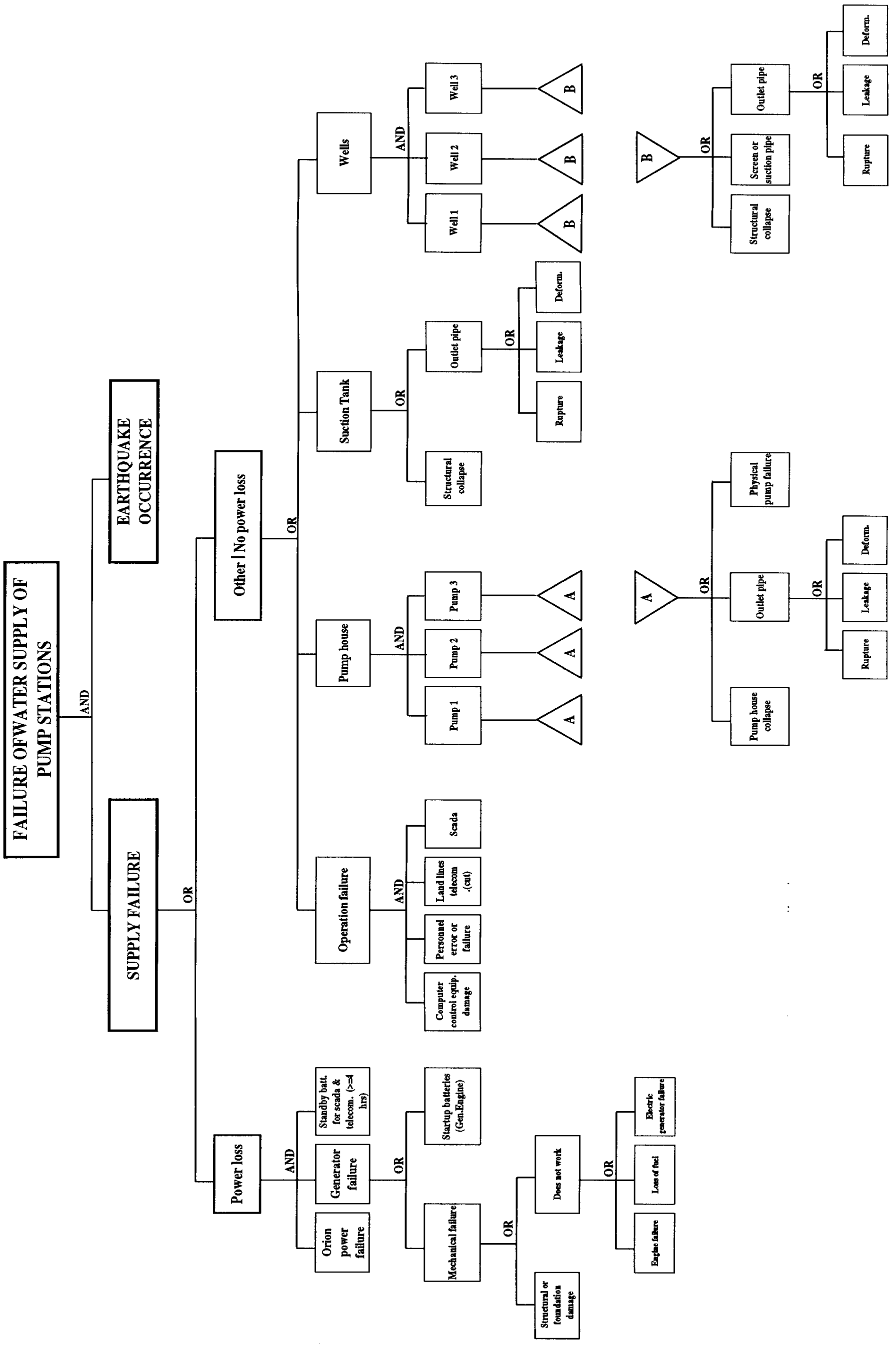

Figure 2. Fault Tree

Risk Balancing for a single pump station

The following example illustrates the risk balancing method applied to a pump station. The modes of failure and the modes of expenditure are as follows

Modes of Failure:	Modes of Expenditure:
For i=1; Administration building	For j=1; Structural upgrade
For i=2;Pump house	For j=2; Power supply upgrade
For i=3; Suction tank	For j=3; Control system upgrade

For i=4; Wells For j=4; Equipment and contents restraints upgrade

Inputs

a_j^0 =

45,000	20,000	10,000	55,000

Table 1

p_i^0 =

0.10
0.20
0.20
0.05

r_{ij} =

0.05	0.06	0.06	0.03
0.10	0.10	0.05	0.05
0.10	0.00	0.00	0.03
0.02	0.02	0.01	0.01

Table 2

c_i =

60,000
40,000
40,000
20,000

u_{ij} =

3,000	3,000	20,000	5,000
5,000	5,000	2,000	30,000
10,000	1	1	5,000
5,000	1,000	500	1,000

Results

The solution was carried out for a number of different amounts of total expenditure C to investigate the sensitivity of the result to changes in scale. The results are shown in Figure 3. It can be seen that for the figures adopted for the exercise, then initially, for low values of C, the greatest expenditure should be in modes 1 and 2. However, this changes quite quickly with increase in C, stabilising to a relatively constant proportion for expenditures greater than $200,000.

Hence for low budget, emphasis should be given to upgrading the structure (mode 1) and the power supply (mode 2). For larger budgets, expenditure should be roughly in proportion 1 : 2 : 2.5 : 3.5 for modes 2,1,3 & 4 respectively. However, there is something clearly wrong with these results from a practical point of view because restraints cost relatively little and should be in practice the first thing to be attended to even with a small total budget. For this reason, as mentioned earlier, the results should be seen merely as illustrations of the use of the method and no weight should be given to the actual values in practice. Though many of the input values were made as realistic as possible, others had at this stage to be estimated very roughly. More work is needed in refining the example and calibrating it against the practical situation.

In practice, of course, expenditure does not vary smoothly. One spends $200,000 on a piece of equipment or nothing at all. Nevertheless, the results can be used as a general guide. The technique is deliberately framed in a way that cannot be misinterpreted as having an unjustified precision.

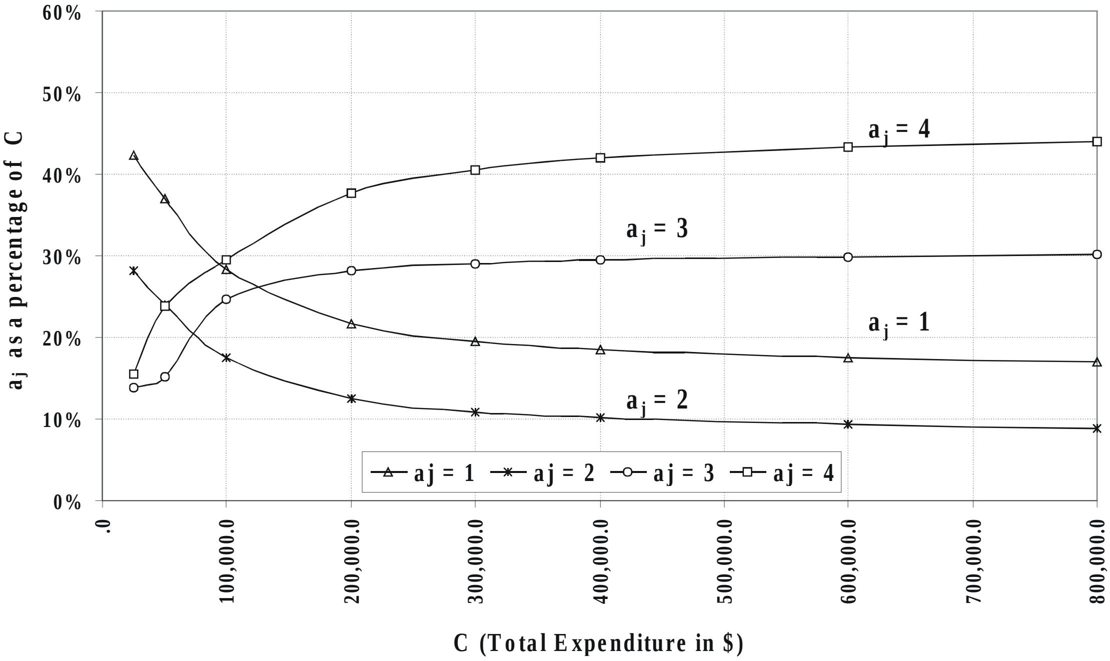

Figure 3. Variation in Relative Modal Expenditures

Uncertainty Analysis

Because of the uncertainty in the input parameters, it is important to investigate the sensitivity of the results to changes in the input parameters. By using @Risk (Palisade Corporation 1995), different probability distributions have been used to represent uncertainties in the input parameters. A truncated lognormal distribution is used for the probability of failure and for the limiting probability reduction. A lognormal distribution is used for the cost consequences and standard reduction expenditure. A latin hypercube simulation is then carried out and the outputs (the final amount spent in expenditure mode j) are expressed as means and standard deviations. The results are shown in Table 3.

Table 3. Simulation results including uncertainty

Item	aj = 1	aj = 2	aj = 3	aj = 4
Mean =	58737.88	33270.27	86669.63	121322.2
Std Deviation =	7096.391	3920.293	10154.69	10686
Cov =	0.12081456	0.11783172	0.11716549	0.08807951

The coefficient of variation is of the order of 0.1 for all modes in this instance. It is also useful to consider a sensitivity of the results to variation of the inputs. Though this has been done, for reasons of space, the analysis is not shown here.

CONCLUSION

A appropriate risk management methodology is presented for optimum allocation of financial resources to lifelines. The methodology can be utilised by a range of decision-makers to control lifeline vulnerability. Use of the technique is illustrated by applying it to the seismic risk to water supply in Christchurch, New Zealand.

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