Benefit-Cost Analysis of Acquisition of Properties Subject to One-time-loss (Landslides)

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For a special class of hazards such as severe landslides, the expected level of damage is usually limited to two possibilities; zero damage or total loss ("one-time-loss"). A new approach is developed for Benefit-cost Analysis of acquisition of properties subject to non-recurring total loss. The equivalent annual probability of landslide is estimated for a given probability of a catastrophic landslide event within the next few years from geotechnical studies. The theoretical approach and assumptions are laid out and the proposed solution is explained through an example problem. Simplified solutions in tabular, graphical and equation formats are included.

INTRODUCTION AND PREVIOUS RELATED STUDIES

The Federal Emergency Management Agency (FEMA) offers simplified approaches to landslide Benefit-Cost Analysis (BCA). FEMA has divided the landslide hazard into two categories: imminent and non-imminent risk. The BCA of properties subject to imminent risk usually amounts to a simple comparison of the acquisition cost (sometimes taken to be the same as Building Replacement Value, BRV) and the cost of contents, displacement, emergency response, and life-safety benefits per occupant. This calculation can be carried out in FEMA's Landslide Acquisition Benefit-Cost Spreadsheet. For non-imminent risk two simple approaches are suggested. The first approach is to use a project life equal to the life of the structure and perform the BCA with a recurring damage method. A second approach is related to the projects with an Annual Rate of Erosion. The initial step is to determine the rate or level of bank erosion that would result in failure of nearby buildings. The BCA can then be conducted based on the assumption that before-mitigation damages caused by erosion can be expected at a recurrence interval (frequency) equal to the time period at which damage occurs based on the erosion rate. However, the above approaches lack strong theoretical justification.

Very few studies are found in literature that directly address the cost effectiveness of acquisition of properties subject to one-time-loss hazard. Zomorodi (2013) offered an approach for when progressive erosion of river bank or road side material due to flooding events of given recurrence interval could trigger the total loss of a property.

Salbego et.al. (2015) studied large-scale cost/benefit analyses of landslide prevention vs. post-event actions. This work focuses on raising awareness and knowledge on prevention benefits and landslide risk reduction.

In an online article available through the Indian Institute of Technology website, Roth and Keaton (2008) discussed the topic of insurance for landslide damages. The authors, one an actuary and one an engineer, point out the complexity in quantifying landslide risk as a prime reason why there are no insurance policies available for landslides. They stress the "vital importance that professional geologists and engineers can make in mitigating landslide damage in an era of rapid development, changing climate, and increasing exposure of valuable infrastructure to potential damage."

Boonyanuphap (2013) performed cost-benefit analysis of very large-scale rehabilitation measures for landslide-damaged in Thailand. The measures included in the analysis aim at reducing or preventing landslide-debris flow. The Net Present Value (NPV) of various measures were estimated. However, acquisition or buy-out of properties at risk were not considered in that study.

This study is conducted to offer a detailed viable approach to performing the BCA under non-recurring damage conditions. The approach applies when the probability of a catastrophic landslide within the next few years can be estimated. The general approach and ground work were previously laid out by Zomorodi (2018).

THEORETICAL APPROACH AND SOLUTION

The BCA of acquisition of properties subject to landslide hazard can be simplified by assuming a "one-time-loss" scenario in which the total loss of the building (usually estimated by BRV) and its contents occur and there is a given cost of displacement of the inhabitants of the property but no injury or life losses. There would be no other damages due to hazards of larger or smaller intensity. In any given year, the property either experiences no loss or total loss. Total loss in this context does not necessarily mean a total destruction of the building and all of its contents. Total loss is usually defined as a level of loss that makes the repairs economically unjustified. According to FEMA's standards, damages to a property over the 50% threshold may be considered as total loss. When a landslide loss occurs, it may be assumed that the land and the property will not be restored to prevent future losses. Furthermore, it is assumed that the probability of the occurrence of the landslide in any given year (P) is a known value between 0.0 and 1.0 which remains constant for each year of the life of the property unless and until the possible failure occurs from which point the hazard is eliminated (the way to estimate this probability is discussed later). Hence, the problem can be categorized as a success-failure scenario and it must be formulated such that the total expected number of failures during the project life does not exceed one and the total damage over the analysis period does not exceed the total damage associated with one-time loss. The binomial process with a probability of success (no-damage) of (1-P) and probability of failure of (P) in Negative Binomial distribution was selected to formulate the problem. Negative Binomial Distribution calculates the probability that there will be a given number of failures before the first, second, third, or the N-th number of success, when the constant probability of a success is 1-P. Negative Binomial Distribution is similar to the more common Binomial Distribution, except that the number of successes is fixed, and the number of trials is variable. Trials are assumed to be independent of each other and the failure probability at a given year (P) is constant.

The Negative Binomial Function for our problem can be written as:

$$NB\left(x,r,P\right)=\frac{(x+r-1)!}{(x)!(r-1)!}P(1-P)^{N} \tag{1}$$

where,

"x" is the number of failures (for "one-time-loss" x would be either 0 or 1 to signify landslide or no landslide);

"r" is number of successes (number of years with no landslide);

"P" is the probability of landslide in any given year (equivalent annual probability of failure);

"N" is the number of successive trials (for our case we can treat N as the minimum between the building useful life and the project useful life. According to FEMA guidelines for acquisition projects the project useful life may be taken as 100 years. Note that the probability of no failure up to a given year depends on the year in consideration (N). For example, if we set x to zero and r to 5 and N to 5 and P to 0.2057, Equation 1 gives a value of 0.316 as the probability of no failure within the first five years of analysis given the equivalent annual failure probability of 0.2057.

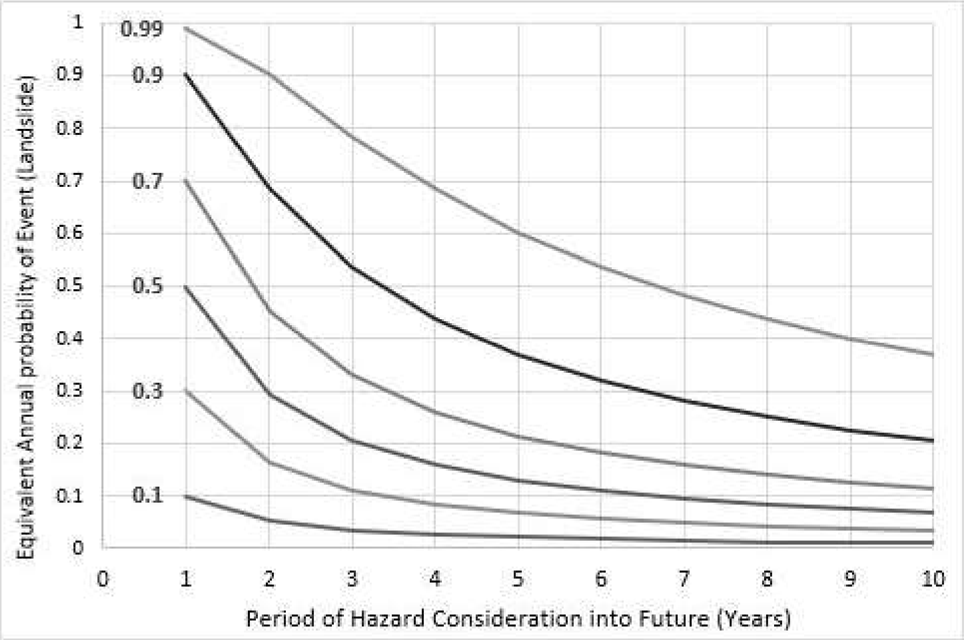
Equation 1 was implemented in a BCA module written in an Excel spreadsheet to enable estimating the Benefit-cost Ratio (BCR) of an acquisition project subject to "one-time-loss" hazard. The solution method involves estimating an equivalent annual probability of landslide. The probability of landslide in any given year may be estimated based on rainfall probabilities using approaches such as the approach summarized in Baum et.al. (2010) and using software such as USGS's TRIGRS (USGS 2009) which is a computer program for time-dependent slope stability in response to rainfall infiltration. Other potentially useful tools include TinSAR Slope Monitoring (radar system), USGS's Scoop3D software to analyze three-dimensional slope stability throughout a digital landscape, and USGS Landslide Hazard Program and National Landslide Hazard Map. Landslide susceptibility analysis which is commonly performed in many countries could set landslide hazard probabilities with a regional or local scale.

An estimate of an equivalent annual probability of failure (e.g. landslide destroying the building) can be evaluated based on annualized probability by the following equation:

$$P = 1 - (1 - P_n)^{(1/n)} \tag{2}$$

where P is the equivalent annual probability of failure (landslide) and "n" is the time period in years (period of hazard consideration, typically the next few years) and P_n is the cumulative probability of failure during the period "n". Figure 1 plots the equivalent annual probability of failure as a function of future period in years (X-axis) and cumulative probability of failure within the given period which is given as the label for each curve.

FIGURE 1
EQUIVALENT ANNUAL PROBABILITY OF FAILURE AS A FUNCTION OF FUTURE PERIOD (X-AXIS) AND CUMULATIVE PROBABILITY OF FAILURE WITHIN GIVEN PERIOD (CURVE LABEL)



The spreadsheet calculations are explained here through an example problem. Table 1 shows the input/output section of the spreadsheet populated with an example problem. Suppose a building is subject to non-imminent threat of landslide and the problem parameters are as shown under the input section in Table 1. The geotechnical analysis predicts a 90% chance of failure within the next 10 years (P_n= 0.9 and n= 10), the equivalent annual probability of failure or P would be 0.2057 corresponding to an equivalent recurrence interval of 4.86 years. Notice that the derivation of Equation 2 assumes independent and stationary probability of failure from year to year which may not be fully applicable to the landslide hazard. However, this equation works consistently with the Negative Binomial function used in Equation 1 to provide a practical solution for estimating annual probability of failure. For the example mentioned above, the distribution of annual failure probability by Negative Binomial distribution would create annual probabilities that start at 0.20567 for the first year and decrease to 0.02589 for the tenth year while the sum of the annual probabilities for the ten years would add up exactly to 0.90, the input for the probability of failure within 10 years.

TABLE 1
EXAMPLE LANDSLIDE BCA PROBLEM AND SOLUTION

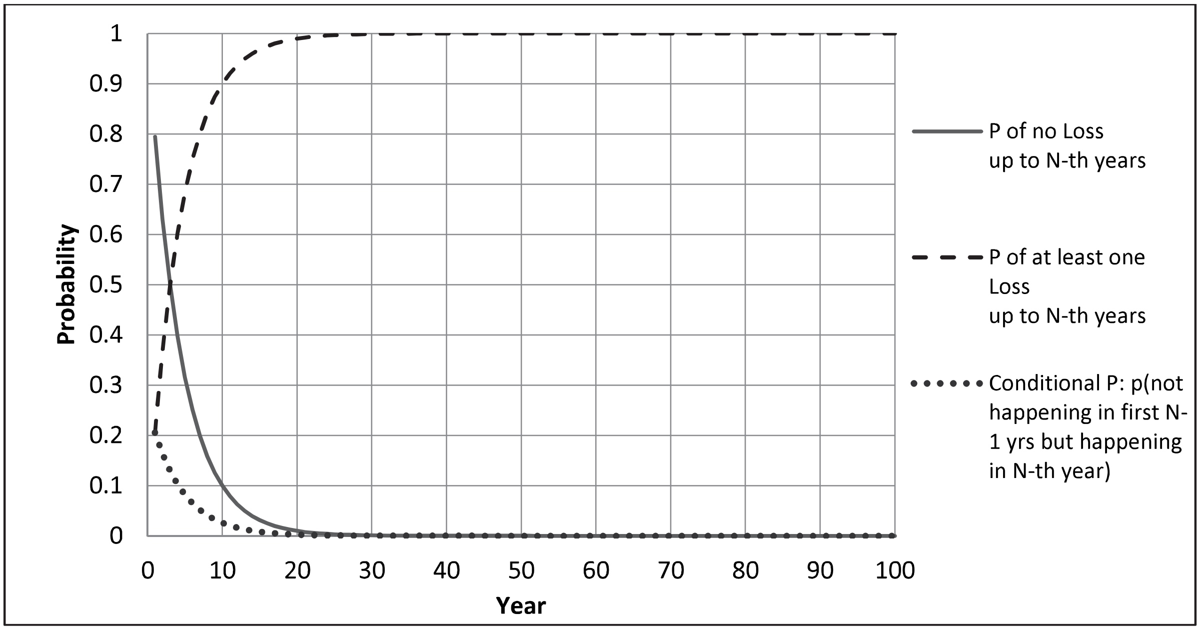
Input (blue cells)		**Results**	
Period of Hazard considered (years) ------------->	**10**	Equivalent Annual probability of event (landslide) resulting in total loss ---------------------->	**0.2057**
Probability of catastrophic event within above time	**0.9**	Equivalent Return Period of event (landslide) resulting in total loss --------------------->	**4.86**
BRV --------------->	**$100,000**	Total damage ---------------->	**$140,000**
Contents --------->	**$30,000**	Sum of potential damages over shorter of the building and project lives ----------------->	**$140,000**
Displacement cost->	**$10,000**	Sum of Present Value of avoided damages over shorter of the building and project lives ----->	**$104,450**
Mitigation cost--->	**$100,000**	**BCR =**	1.04
building Useful life (years) ------->	**100**	program uses the minimum of building and project useful life	
Mitigation Project Useful Life (years) ->	**100**		

Table 2 displays the first ten rows (10 out of 100 years of project life) of calculations. In the second column, the Negative Binomial Function is calculated to establish the probability of zero failures (no landslides) up to the given year. For the first year this probability is just equal to 1- P (0.7943 in this case). However, for consequent years this probability decreases gradually as shown in Figure 2. For example, the value decreases to 0.10 for Year 10 meaning that there is about 10% chance that there will be no landslides in the first ten years which confirms the initial assumption of 90% chance of failure in the next ten years. The probability of no failure by the 100th year reaches an extremely low value (virtually zero). This means that in our calculations we are capturing the probability distribution of almost one failure and certainly no more than one failure.

TABLE 2
THE FIRST TEN ROWS OF THE EXAMPLE LANDSLIDE BCA CALCULATIONS

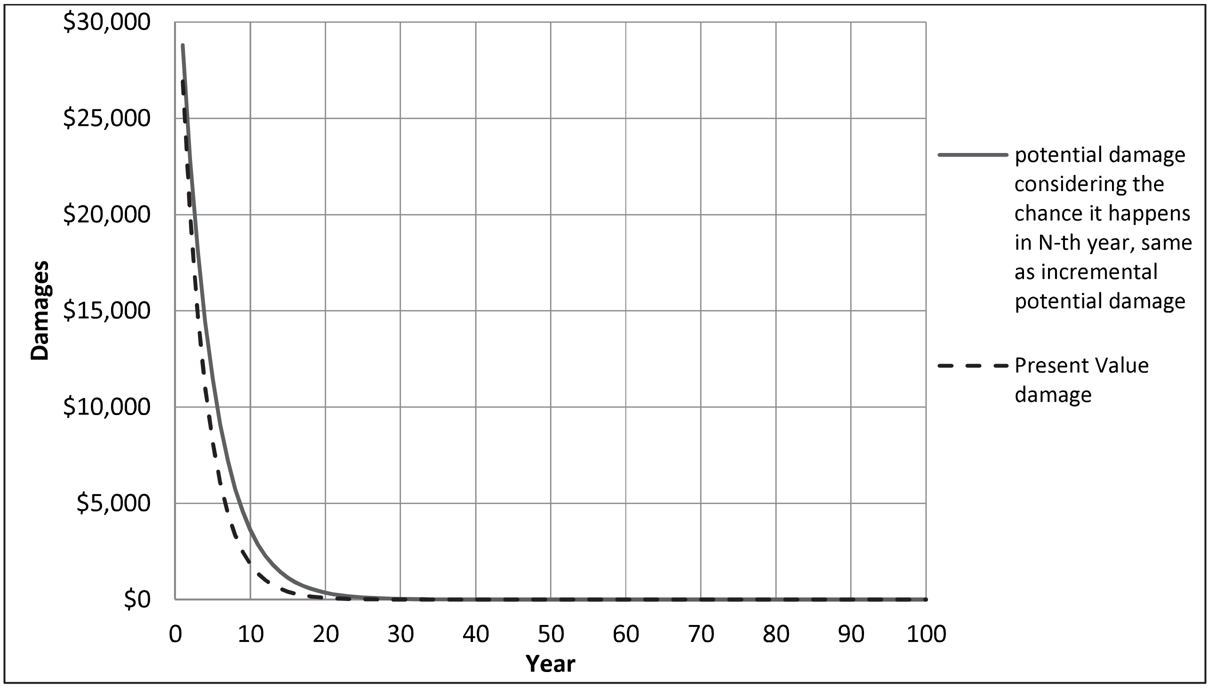
N	P of no Loss up to Nth years	P of at least one Loss up to N-th years	total potential damage up to n years if recurring	Conditional P: p(not happening in first N-1 yrs but happening in N-th year)	potential damage considering the chance it happens in N-th year, same as incremental potential damage	Present Value damage
1	0.79433	0.20567	$28,794.05	0.20567	$28,794.05	$26,910.32
2	0.63096	0.36904	$51,665.97	0.16337	$22,871.92	$19,977.22
3	0.50119	0.49881	$69,833.79	0.12977	$18,167.82	$14,830.35
4	0.39811	0.60189	$84,265.00	0.10308	$14,431.21	$11,009.50
5	0.31623	0.68377	$95,728.11	0.08188	$11,463.12	$8,173.04
6	0.25119	0.74881	$104,833.59	0.06504	$9,105.48	$6,067.36
7	0.19953	0.80047	$112,066.33	0.05166	$7,232.74	$4,504.19
8	0.15849	0.84151	$117,811.50	0.04104	$5,745.17	$3,343.74
9	0.12589	0.87411	$122,375.04	0.03260	$4,563.55	$2,482.27

FIGURE 2
PROBABILITIES ESTIMATED OVER NEXT 100 YEARS



Column 3 in Table 2 shows the complementary probability to column 2 or the probability of at least one landslide up to the given year. This probability starts at 0.20567 but gradually increases according to Figure 2 and by the 100th year practically reaches one. The forth column calculates the total potential damage up to the given year if the landslide damage was recurring. These values are of little use for our calculations that are concerned with non-recurring damages. However, it is informative to know that the sum of these damages over the next 100-years amounts to $13,459,304. From this it is easy to see why we should no consider this hazard as a recurring event. The fifth column calculates the conditional probability of the landslide happening in the N-th year given the condition that it does not occur in the first N-1 years. This probability starts as 0.20567 for the first year and is calculated as the difference between the consequent numbers in either the second or third column. For example, the probability of a landslide during the fifth year years is 0.08188 and it drops down to 0.02589 by the 10th year. Theses conditional probabilities are shown as the lower curve in Figure 2. This calculation ensures that the probability distribution of no more than one landslide during the project life is considered. For this example, the sum of these numbers over the 100 years of project life is very nearly 1.0 which indicates the fact that the period of 100 years is sufficient to represent the benefits of an acquisition project. The sixth column in Table 2 shows the values of the potential damage considering the chance it happens in the given year if not already happened previously. These incremental potential damages are evaluated by multiplying the values in column 5 by the total damage and are displayed as the upper curve in Figure 3.

FIGURE 3
INCREMENTAL POTENTIAL DAMAGES AND THEIR PRESENT VALUES



The sum of these values over 100 years is $140,000 which is the same as the total damage of one-time-loss. This means that we are only considering the damages of only one potential failure but merely assigning a statistical time distribution to that damage figure. We then need to assign a present value to damages happening at different times from now. The last column of Table 2 gives the present value of the future damages in the sixth column based on a discount rate of 7% (Standard FEMA value for BCA). The values in the last column of Table 2 are also shown in Figure 3 as the lower curve in broken line. Figure 3 show that, in this case, the present value of total avoided damages beyond 25-years approaches zero. The sum of the present value of avoided damages over 100 years of project life (sum of the values in the last column of Table 2) is $104,450 which can be assigned as the project benefit and be compared with the mitigation (acquisition cost) of $100,000 to calculate the Benefit-Cost Ratio (BCR) of this project to be 1.04 as shown in Table 1.

BCR Tables

The spreadsheet calculations as laid out above were used to generate tables for quick evaluation of cost-effectiveness of landslide acquisition or similar mitigation projects that deal with non-recurring hazards resulting in total property loss. To construct the BCR tables, the problem parameters are grouped together. The first parameter is the ratio of total Damage to Mitigation Cost (DR). The second parameter is the annual probability of hazard (landslide) or P and the third parameter is the project life. A BCR table may be constructed for any project life (or building useful life). For brevity only the table for the 100-year project life, which is the FEMA default value for acquisition projects, is presented as Table 3 here. The DR parameter in Table 3 changes from 1.0 to 2.0 and P ranges from 0.05 (20-year return period) to 0.50 (2-year return period) and the value of 0.99 is also given for reference. Sample calculations showed that the 50-year project life has very similar results to the 100-year project life. Table 3 shows that for a landslide acquisition project to be cost-effective (as indicated by BCR values greater than one shown in bold font in Table 3), the probability of landslide should be relatively high and/or the ratio of the total damages to the mitigation cost should be relatively high. For example, for a project with P= 0.1, DR must be more than 1.7, meaning that the cost of building contents plus displacement cost should be more than 70% of the BRV. As P increases, the minimum required DR to make the project cost-effective decreases.

TABLE 3
BCR TABLE FOR ACQUISITION OF PROPERTIES SUBJECT TO NON-RECURRING HAZARD

BCR Values for Non-recurring damages, Hazard results in Total Loss, Mitigation= Acquisition, Minimum between the Project and Building Useful Life is **100** Years.

Annual probability of landslide resulting in total loss (P)

		0.050	0.075	0.100	0.125	0.150	0.175	0.200	0.225	0.250	0.300	0.350	0.400	0.500	0.990
Total Damage / mitigation cost (DR)	1	0.42	0.52	0.59	0.64	0.68	0.71	0.74	0.76	0.78	0.81	0.83	0.85	0.88	0.93
	1.05	0.44	0.54	0.62	0.67	0.72	0.75	0.78	0.80	0.82	0.85	0.87	0.89	0.92	0.98
	1.1	0.46	0.57	0.65	0.71	0.75	0.79	0.81	0.84	0.86	0.89	0.92	0.94	0.96	**1.03**
	1.15	0.48	0.59	0.68	0.74	0.78	0.82	0.85	0.88	0.90	0.93	0.96	0.98	**1.01**	**1.07**
	1.2	0.50	0.62	0.71	0.77	0.82	0.86	0.89	0.92	0.94	0.97	1.00	**1.02**	**1.05**	**1.12**
	1.25	0.52	0.65	0.74	0.80	0.85	0.89	0.93	0.95	0.98	**1.01**	**1.04**	**1.06**	**1.10**	**1.17**
	1.3	0.54	0.67	0.76	0.83	0.89	0.93	0.96	0.99	**1.02**	**1.05**	**1.08**	**1.11**	**1.14**	**1.21**
	1.35	0.56	0.70	0.79	0.87	0.92	0.96	1.00	**1.03**	**1.05**	**1.09**	**1.13**	**1.15**	**1.18**	**1.26**
	1.4	0.58	0.72	0.82	0.90	0.95	1.00	**1.04**	**1.07**	**1.09**	**1.14**	**1.17**	**1.19**	**1.23**	**1.31**
	1.45	0.60	0.75	0.85	0.93	0.99	**1.04**	**1.07**	**1.11**	**1.13**	**1.18**	**1.21**	**1.23**	**1.27**	**1.35**
	1.5	0.62	0.78	0.88	0.96	**1.02**	**1.07**	**1.11**	**1.14**	**1.17**	**1.22**	**1.25**	**1.28**	**1.32**	**1.40**
	1.55	0.65	0.80	0.91	0.99	**1.06**	**1.11**	**1.15**	**1.18**	**1.21**	**1.26**	**1.29**	**1.32**	**1.36**	**1.45**
	1.6	0.67	0.83	0.94	**1.03**	**1.09**	**1.14**	**1.19**	**1.22**	**1.25**	**1.30**	**1.33**	**1.36**	**1.40**	**1.49**
	1.65	0.69	0.85	0.97	**1.06**	**1.12**	**1.18**	**1.22**	**1.26**	**1.29**	**1.34**	**1.38**	**1.40**	**1.45**	**1.54**
	1.7	0.71	0.88	1.00	**1.09**	**1.16**	**1.21**	**1.26**	**1.30**	**1.33**	**1.38**	**1.42**	**1.45**	**1.49**	**1.59**
	1.75	0.73	0.91	**1.03**	**1.12**	**1.19**	**1.25**	**1.30**	**1.33**	**1.37**	**1.42**	**1.46**	**1.49**	**1.54**	**1.63**
	1.8	0.75	0.93	**1.06**	**1.15**	**1.23**	**1.29**	**1.33**	**1.37**	**1.41**	**1.46**	**1.50**	**1.53**	**1.58**	**1.68**
	1.85	0.77	0.96	**1.09**	**1.19**	**1.26**	**1.32**	**1.37**	**1.41**	**1.45**	**1.50**	**1.54**	**1.57**	**1.62**	**1.73**
	1.9	0.79	0.98	**1.12**	**1.22**	**1.30**	**1.36**	**1.41**	**1.45**	**1.48**	**1.54**	**1.58**	**1.62**	**1.67**	**1.77**
	1.95	0.81	**1.01**	**1.15**	**1.25**	**1.33**	**1.39**	**1.44**	**1.49**	**1.52**	**1.58**	**1.63**	**1.66**	**1.71**	**1.82**
	2	0.83	**1.03**	**1.18**	**1.28**	**1.36**	**1.43**	**1.48**	**1.53**	**1.56**	**1.62**	**1.67**	**1.70**	**1.75**	**1.87**

BCR Equations

Because the problem parameters could be conveniently grouped together as described in the previous section, it is possible to provide equations that set the cost-effectiveness conditions for landslide mitigation projects. To derive these equations first a BCR table in more details than in Table 3 was prepared for project life of 100 years. This table provided the minimum DR required for a given P to make the project cost-effective. The results of this analysis and the best fit curve to data are displayed graphically in Figure 4.

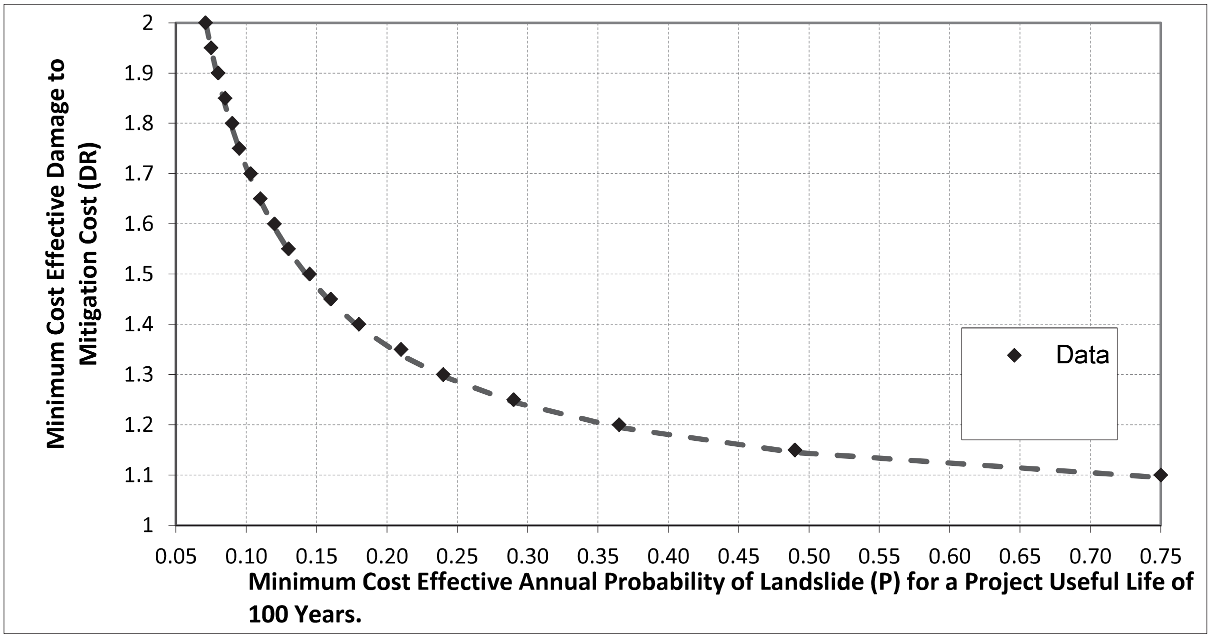
The best fit curve to the data is expressed as the following equation to give the minimum ratio of the total damages to mitigation cost that makes the project cost-effective:

$$DR = 1 + \frac{0.0711}{P} \tag{3}$$

Considering that P is the reciprocal of the return period (Tr), the above equation can also be written as:

$$DR = 1 + 0.0711\, T_r \tag{4}$$

FIGURE 4
RELATIONSHIP BETWEEN P AND DR FOR PROJECT LIFE OF 100 YEARS



Given that DR is the ratio of total Damage to Mitigation Cost, the condition of cost-effectiveness can be also expressed as:

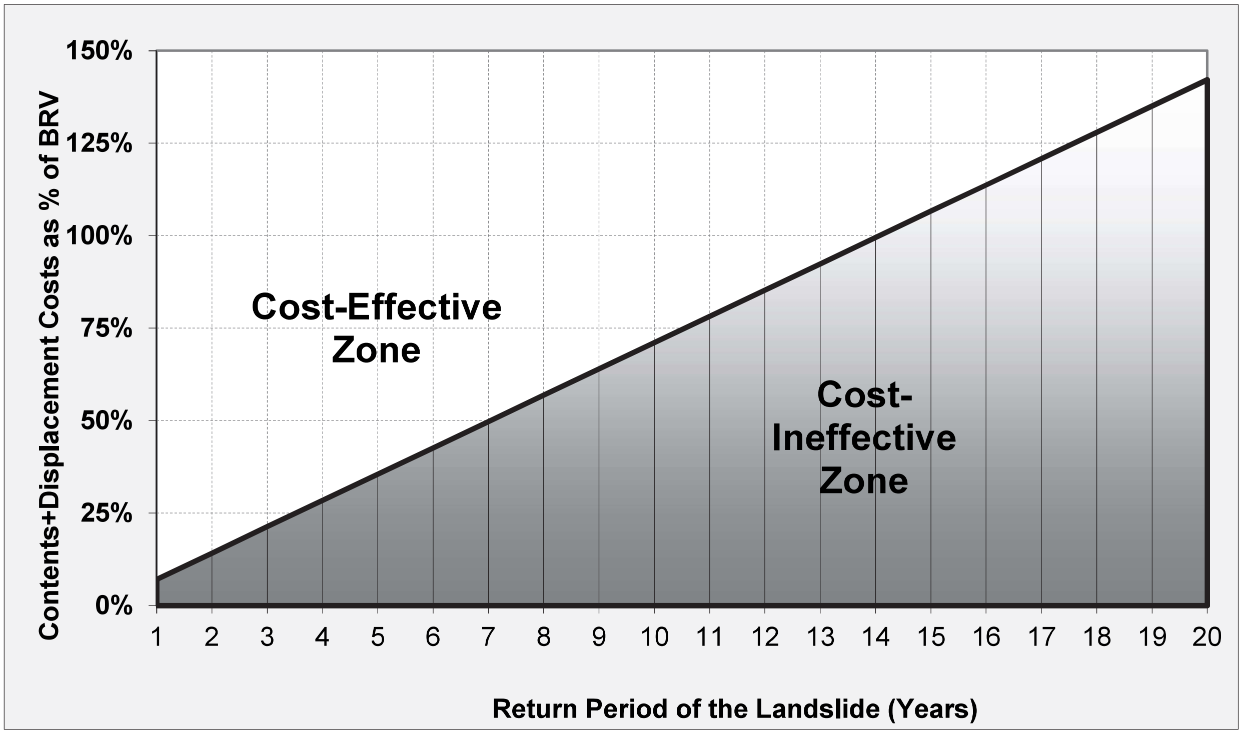
$$TotalDamages \geq (1 + 0.0711\, T_r) \times MitigationCost \tag{5}$$

Assuming the difference between total damages and the BRV (assumed to be the same as project cost) is equal to the contents plus displacement costs, the cost-effectiveness condition can also be expressed as:

$$Contents + DisplacementCosts \geq (0.0711\, T_r) \times BRV \tag{6}$$

The conditions of cost-effectiveness set by the above equations can also be displayed graphically. Figure 5 shows the Cost-effective and Cost-ineffective Zones portrayed on a graph of the return period of the landslide vs. the contents plus displacement cost as a percentage of the BRV. This graph is developed for the structure useful life and the mitigation project life of 100 years. However, the graph is also applicable as long as the project life and structure useful life is 50-years or longer. To use Figure 5, the user enters the graph at X-axis with the return period of the event (landslide causing total loss which is 50% or greater damage according to FEMA) and moves vertically up to a point at the contents plus displacement costs as a percentage of BRV. If the point falls within the cost-effective zone the project is cost-effective. As indicated in Figure 5 for the return period of the landslide greater or equal to 15 years the contents plus displacement costs need to be larger than 100% of building replacement cost.

FIGURE 5
THE COST-EFFECTIVE AND COST-INEFFECTIVE ZONES FOR PROJECT LIFE OF 100 YEARS



SUMMARY AND CONCLUSIONS

This paper presents a new approach to assess the cost effectiveness of acquisition of properties subject to a non-recurring hazard resulting in total loss of the property. A prime example of such hazard is a catastrophic landslide. The proposed approach categorizes the problem as a success-failure scenario and formulates the solution so that the total expected number of failures during the project life does not exceed one and the total damage over the analysis period does not exceed the total loss. The main solution method is coded in a spreadsheet but simplified solutions in tabular, graphical and equation formats are also presented. Example applications of the proposed solution indicate that for a landslide acquisition project to be cost-effective the probability of landslide should be relatively high and/or the ratio of the total damages to the mitigation cost should be relatively high.

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