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Tolerable risk chart

Diagramme des risques tolérables

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ABSTRACT: Risk R is defined here as the product of the probability of failure P_f times the value of the consequence C. The consequence is typically evaluated in terms of cost or fatalities, or both. Once the risk is estimated for a given infrastructure element, the engineer must decide what value of R is tolerable: what is the tolerable risk? The paper builds on concepts first published by Whitman in 1984 and the original f-n chart also called the "bubble chart". Because of how critically important that chart is, the authors decided to create an updated version of that chart while explaining precisely where the data came from and how the points on the chart were obtained. Among other data, they collected statistics on open pit mine slopes, water retaining dams, bridge scour, nuclear power plants as well as common human factors such as car accidents, airplane crashes, cancer and heart diseases. Using this modern version of the f-n chart the authors advocate that risk values of 0.001 fatalities/year and $10,000/year are reasonably tolerable as they are consistent with other daily human activities tolerated by the general public. The use of this chart is not limited to geotechnical engineering but has broad applications to any major engineering decision.

RÉSUMÉ : Le risque R est défini ici comme le produit de la probabilité de défaillance P_f par la valeur de la conséquence C. La conséquence est généralement évaluée en termes de coût ou de décès ou les deux. Une fois le risque estimé pour un élément d'infrastructure donné, l'ingénieur doit décider quelle valeur de R est tolérable: quel est le risque tolérable? Le document s'appuie sur les concepts publiés pour la première fois par Whitman en 1984 et sur le graphique f-n original également appelé «graphique à bulles». En raison de l'importance critique de ce graphique, les auteurs ont décidé de créer une version mise à jour de ce graphique tout en expliquant précisément d'où provenaient les données et comment les points du graphique ont été obtenus. Entre autres données, ils ont recueilli des statistiques sur les pentes des mines à ciel ouvert, les barrages de retenue d'eau, l'affouillement des ponts, les centrales nucléaires, ainsi que les facteurs humains courants tels que les accidents de voiture, les accidents d'avion, le cancer et les maladie du coeur. En utilisant cette version moderne du graphique f-n, les auteurs soutiennent que les valeurs de risque de 0,001 décès / an et de 10,000 $ / an sont raisonnablement tolérables car elles correspondent à d'autres activités humaines quotidiennes tolérées par le grand public. L'utilisation de cette carte n'est pas limitée à l'ingénierie géotechnique, mais a de larges applications à toute décision d'ingénierie majeure.

KEYWORDS: Geotechnical risk, tolerable risk, f-n chart, open pit mines, earth dams

1 INTRODUCTION.

This paper aims to help inform engineers, decision-makers, and the public of the risk associated with infrastructure projects. This is done by updating a risk chart first proposed by Whitman and his colleagues at MIT starting in 1984 (e.g.: Whitman (1984), Baecher and Christian (2003), Gilbert (2017), Griffiths and Fenton (2008), Phoon (2008)).

In civil engineering practice, the risk R associated with a project, is defined as the product of the probability of failure P_f of that project times the value of the consequence C of the failure (Eq. 1).

$$R = P_f \cdot C \tag{1}$$

The probability of failure P_f can be represented as the product of the probability of occurrence of an event that might cause the failure (*e.g.*: flood, earthquake, overload), $P(E)$, by the probability of failure if that event occurs $P(F/E)$ also called vulnerability or fragility (Eq. 2).

$$P_f = P(E) \cdot P(F/E) \tag{2}$$

As an example, if the annual probability that the failure will occur is 0.002 and if the value of the consequence is 5 fatalities and a cost of US$1,000,000, the risk is 5·0.002=0.005 fatalities/yr and 1,000,000·0.002=$2,000/yr. So, the units of Risk will be in fatalities per year and US dollars per year.

Equation 1 can be modified by taking the decimal logarithm of the parameters:

$$\log P_f = \log R - \log C \tag{3}$$

Therefore, for a constant risk the graph of the annual probability of failure P_a versus the value of the consequence C on log scales will be a straight line with a slope of -1. That line is depending on the chosen value of the annual risk R (Fig. 1). The width of the ellipse represents the range of the consequence values while the point near the center represents the mean value.

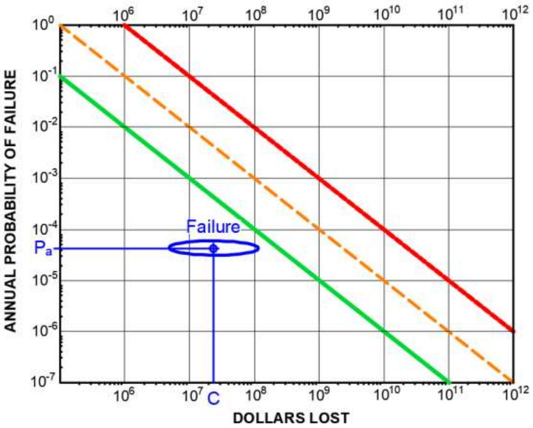

Figure 1 – Example of the risk chart; the location of the activity has coordinates of P_a and C.

2 PROCEDURE

A number of activities were selected to show their location on the risk chart. These activities were

1. Car accidents
2. Cancer

3. Heart disease and stroke
4. General aviation
5. Commercial aviation
6. Nuclear power plants
7. Bridge scour
8. Open pit mine slopes
9. Earth dams

The general step-by-step procedure for obtaining the risk location of a given activity on the chart was as follows:

1. Define the failure phenomenon (for example, earth dam failure)
2. Collect information to determine the total number of failures F_t over n years (for example, 30 years).
3. Obtain the average annual number of failures F_a given by F_t/n.
4. Collect information to determine the total number S of structures or people involved with the activity in the inventory (for example, total number of dams in the US or total number of people in the US).
5. Calculate the average annual probability of failure P_a as F_a/S and the range of P_a values for the study period.
6. Collect the number of people that died for each documented failure for the period of n years. Add those up to obtain the total number of fatalities D over the period of n years and for F_t failures.
7. Obtain the average number of fatalities X corresponding to one failure as D/F_t and the range of X values for the study period. Note that, because of the log scale, the ellipse created for each activity was bound by 0.01 fatalities if the lower bound was 0.
8. Collect the consequence cost associated with each failure for the period of n years. Convert these values into US 2020 dollars by correcting for inflation. Add those up to obtain the total cost c of those failures over n years and for F_t failures.
9. Obtain the average cost C associated with each failure as c/F_t and the range of C values over the study period.
10. The location of the activity has coordinates of P_a and X on the fatality risk chart and P_a and C on the cost risk chart.

3 APPLICATION TO VARIOUS ACTIVITIES

The authors analyzed the risk associated with different public and civil engineering activities. They are Car accidents, Cancer, Heart disease and stroke, General aviation, Commercial aviation, Nuclear power plants, Bridge scour, Open pit mine slopes and Earth dams. Table 1 summarizes the results obtained.

3.1 *Car accident*

According to the statistics published by the National Highway Traffic Safety Administration (NHTSA) there were 36,096 lives loss on US roads in 2019 (NHTSA, 2020). Since there are approximately 2.8 million deaths every year in the US. car accidents account for approximately 1.3% of total deaths in the US.

First, let's define the failure as a 'car accident fatality'. The statistical data for the period of 1994-2018 (*n*=25 years) were analyzed. During that period the total number of failures is F_t=973,698, therefore the annual number of deaths due to car accidents averaged F_a=973,698/25=38,948 (NHTSA, 2020). The average number of people in the United States from 1994 to 2018 was S=297 million (U.S. Census Bureau, 2020). Therefore, the annual probability of a person dying in a car accident in the US is P_a=38,948/(2.97·10^8)=1.31·10^{-4}, the fatality consequence X is 1 and the economic loss C is taken as 1 million dollars, because that is a reasonable average for the life insurance carried by many people (Briaud, 2013).

If we defined failure as 'a car accident with fatality' then the annual probability of a fatal car crash can be calculated as follows. During the period of 25 years the total number of failures was F_t=880,656, thus the annual number of fatal car accidents in the US was F_a=880,656/25=35,226 (NHTSA, 2020). The average annual number of registered vehicles in the US is S=243.5 million (Statista, 2020). According to the National Household Travel Survey (FHWA, 2020), the average light vehicle occupancy is 1.67 for the past 25 years. The economic loss of traffic crashes for the same period was US2020$ c=319.2 billion (NHTSA, 2020). Therefore, the annual probability of a fatal car crash is P_a=35,226/243,500,000=1.45·10^{-4}, the corresponding number of fatalities X is 1.67 and the economic loss C is 9.1 million dollars ($319,200,000,000/35,226). Figures 2 and 3 show the data associated with car accidents.

3.2 *Cancer*

Malignant neoplasms (cancer) is the second leading cause of fatalities in the US accounting for 21.3% of all deaths (CDC, 2020). The failure is defined as 'a person dying of cancer'. The probability to die of cancer was estimated based on the statistical data from 1996-2018 (*n*=24 years). According to the American Cancer Society (2019), each year an average of F_a=570,034 people die of cancer in the US. There were S=301 million people on average in the US over that period of 24 years (U.S. Census Bureau, 2020). Therefore, the annual probability of failure associated with cancer is P_a=570,034/301,000,000 =1.89·10^{-3}, and the fatality consequence is X=1. Also according to the American Cancer Society (2019) report, the total cost of cancer over the last 20 years is US2020$ c=135.2 billion. Thus, for an individual, the annual economic loss is calculated to be US2020 $237,179 ($135,200,000,000/570,034). The data associated with cancer is located in Figs. 2 and 3.

3.3 *Heart Disease and Stroke*

Heart disease is the number one cause of death in the US and accounts for 23% of all deaths (NVSS 2019, CDC 2020). The failure phenomenon is defined as 'a person dying of a heart disease'. During the period 2006-2018 (*n*=13 years) there were F_t=8,054,019 fatalities, corresponding to an average fatality per year of F_a=619,540·(8,054,019/13). The annual probability of death due to heart disease is P_a=619,540/313,000,000=1.98·10^{-3}, because S=313 million is the average number of people in the US for the period 2006-2018. The life lost is X=1.

Stroke is one of the five leading causes of death in the United States. The failure is 'a person dying of a stroke'. Based on the statistical data for the period of 1999-2018 the total number of deaths was F_t=2,874,333, and the annual number of deaths due to stroke is F_a=143,717. The average US population for the same period is S=304 million. Therefore, the annual probability to die due to a stroke is P_a=143,717/304, 000,000=4.73·10^{-4}, and the life lost is X=1. Fig. 2 shows the data associated with heart disease and stroke separately.

The probability to die due to a stroke or heart disease is obtained by combining the statistics for both diseases. The annual number of death due to stroke or heart disease for the last 13 years is F_a=755,059, therefore P_a=2.41·10^{-3}. The total direct and indirect cost of heart disease and stroke in the United States for the studied period is estimated at US2020 c=$368 billion (AHA, 2018). The annual economic loss corresponding to one fatality is therefore US2020 C=$4.95·10^5 (368·10^9/755,059). The combined data associated with the cost of heart disease and stroke is presented in Fig. 3.

3.4 *General aviation*

General aviation accounts for approximately 77% of all aircraft operations in the United States. Approximately 95% of the 220,000 civil aircraft registered in the US are general aviation aircraft (Sobieralski, 2013, Mazareanu, 2020a). General aviation is defined as all flying aircraft excluding military and scheduled airline operations and includes flight training, search and rescue, aerial surveys, crop dusting, and personal/recreational use. Sobieralski (2013) states that general aviation accident and fatality rates are approximately 50 times greater than commercial aviation rates. According to The National Transportation Safety Board (NTSB, 2014) general aviation includes private aviation and operations that employ a wide range of aircraft such as airplanes, rotorcraft, gliders, balloons, and blimps, and registered experimental or amateur-built aircrafts. The vast majority of general aviation accidents involve personal or recreational flights. The Federal Aviation Administration (FAA, 2018) identified the following top three leading causes of fatal general aviation accidents from 2001 to 2016: (a) Loss of Control in flight; (b) Controlled Flight into Terrain; (c) System Component Failure – Powerplant.

The failure in this case is defined as 'a fatal general aviation accident'. According to the data published by the Bureau of Transportation Statistics (2018) the total number of general aviation fatal accidents in the US for the period 2002-2018 (n=17 years) is F_t=4,642. On average there were F_a=273 fatal general aviation plane accidents per year for a total number of flights per year of S=10,187,656. Therefore, the probability of a fatal general aviation plane crash for any given flight is P_a=273/10,187,656=$2.68\cdot10^{-5}$. The total number of fatalities associated with general aviation plane crashes for the same period of time is D=8157, and the average annual number of fatalities per failure is X=8157/4642=1.76.

The cost of general aviation crashes has been studied by a few researchers (Scuffham et al. (2002) and Sobieralski (2013)). According to Sobieralski (2013) the total annual cost of general aviation accidents in the United States is c=4.99 billion dollar; therefore the average cost of one fatal accident is C=18.3 million dollar ($4,990,000,000/273). The general aviation location on the risk charts is shown in Figures 2 and 3.

3.5 *Commercial aviation*

Commercial aviation is defined as scheduled airline operations involving aircraft with more than 10 seats. In the US, a commercial operator is one that has been certified by the Federal Aviation Administration (FAA) under the Code of Federal Regulation (CFR) part 121 (airlines) or CFR Part 135 (commuters) to provide air transport of passengers or cargo.

The failure is defined as 'a plane crash'. According to the statistics published by the Bureau of Transportation Statistics (USDoT, 2019) there were F_t=61 fatal plane crashes for the period of 1990-2018 (n= 29 years) and the number of departures per year was S=9,694,928 in the U.S. The annual number of plane crashes is therefore F_a=60/29=2.10 The probability of a plane crash can be determined as P_a=2.10/9,694,928=$2.17\cdot10^{-7}$.

According to published data (USDoT, 2019) the total number of fatalities for the period 1990-2018 is D=1730, and the annual number of fatalities associated with a commercial plane crash is X=1730/61=28.36. Figure 2 presents the commercial aviation data in terms of number of fatalities.

The cost of airline accidents can be associated with coverage for hull, passenger legal liability, third party liability, and products liability. The annual airline insurance cost in commercial aviation between 2000 and 2018 varied between 2.34 and 59.39 billion US$2020 with a mean of 7.73 billion dollars (Makinen, 2002; Mazareanu, 2020b). Therefore, the cost of one commercial aviation failure is US2020 C=$3.68 billion ($7,730,000,000/2.10). Fig. 3 presents the data connected to a plane crash failure.

3.6 *Nuclear Power Plant*

According to the World Nuclear Association (2020) the US is the world's largest producer of nuclear power, accounting for more than 30% of worldwide nuclear generation of electricity. At the end of December 2019, the US had 96 operating commercial nuclear reactors at 58 nuclear power plant sites in 29 states (Office of Nuclear Energy, 2020)

Sovacool (2009) states that sixty-three accidents have occurred since the Chernobyl disaster in 1986, and 71% of all nuclear accidents (45 out of 63) occurred in the US. Such accidents have involved meltdowns, explosions, fires and losses of coolant. They have occurred during both normal operation and extreme, emergency conditions (such as droughts and earthquakes).

The failure is defined as 'major nuclear reactor failure'. The total number of accidents in the US for the 61-year-period is 67 (Sovacool, 2009), however only four of those can be classified as major nuclear reactor failures (F_t=4): Sodium Reactor Experiment (Los Angeles, California, USA, 1959); SL-1 (Idaho Falls, Idaho, USA, 1961), Enrico Fermi Unit 1 (Frenchtown Charter Township, Michigan, USA, 1966), Three Mile Island (Middletown, Pennsylvania, USA, 1978). The annual number of major failures in the U.S. nuclear industry starting in 1959 is F_a=4/61=0.066. The annual number of working reactors for the period of 1959-2019 (n=61 years) is S=76 (EIA, 2020).

The probability of failure associated with the U.S. nuclear power plants is P_a=0.066/76=$8.68\cdot10^{-4}$. The total number of fatalities associated with major nuclear reactor failures for the studied period is D=3 , therefore the number of fatalities associated with one failure is X=3/4=0.75 (Fig. 2).

Because nuclear power plants are so large and complex, accidents onsite tend to be very expensive. The economic loss of one nuclear reactor failure varies from 21.5 million to 3.1 billion US$2020 (Sovacool, 2009). Therefore, the average cost of one failure in the US is US2020 C=$618.3 million (Fig. 3).

3.7 *Bridge scour*

Bridge scour is the most common cause of bridge collapse during storms and floods in the US. Bridge scour is the loss of soil by erosion due to water flowing around bridge supports. According to statistics collected by NYSDOT between 1970 and 2005 (n=36 years) (Sullivan, 2005; Briaud et.al, 2014), 1377 bridges collapsed during those 36 years for an average rate of one bridge collapsing every 10 days; 60% of the time the collapse is due to bridge scour.

The failure is defined as 'bridge scour failure'. The annual probability of failure is the average number of bridge failures per year over a given period divided by the total number of bridges that exist during that same period. According to the NYDOT database, F_t=765 failures due to scour (hydraulic reason) occurred between 1970 and 2005. According to the US National Bridge Inventory (NBI), about S=500,000 bridges over water existed during that 36-year period (Briaud et al., 2012). Therefore, the annual probability of bridge failure due to scour is P_a=$4.25\cdot10^{-5}$. The number of fatalities due to bridge scour failures from 1970 to 2005 is D=28. This gives an average number of fatalities per bridge failure of X=0.04 (28/765). The total cost of the failure C of an average size bridge was estimated by Briaud et. al. (2012) and varies from US2020 $1.45 million to $18 million for bridge scour failures. This cost includes the bridge repair or replacement cost, the detour cost and the cost of time lost. The estimated risk of 0.04 fatalities/yr, and economic loss for bridge scour failures are used to locate the bridge scour ellipse on Figures 2 and 3.

3.8 *Open pit slope stability*

Open pit mining is an industry where taking a calculated risk is important to improve returns. There were 12,448 surface mining operations in the US in 2019 (NIOSH, 2019). The US surface mining is divided by NIOSH into 5 general groups: coal, metal, nonmetal (which includes the mining of clay, trona, barite, phosphate rock, gypsum, talc, gemstones, and pumice), stone, and sand and gravel operations. Active surface mining operations are distributed among the coal (n=849; 6.8%), metal and nonmetal (n=1,082; 8.7%), and stone, sand and gravel (n=10,517; 84.5%) industry sectors (NIOSH, 2019). According to the data collected by the National Institute for Occupational Safety and Health's (NIOSH) for the past 31 years (1982-2019), slope stability accidents are one of the leading causes of fatalities for U.S. surface mining operations with D=145 miners losing their lives as a result of slope failures.

The failure phenomenon is defined as 'an open pit slope failure in one open pit mine'. Highwall accident statistics from the MSHA database were analyzed for the ten-year period (1990-1999) including incident frequency, degree of injury, nature of injury, equipment involved, coal and non-metal breakdown, worker activity at the time of accident, and other relevant parameters (Bhatt and Mark, 2000). The annual number of slope failures in active open pit mines during those 10 years is F_a=43. The annual number of active surface mines during the same period was S=13,234, therefore the probability of open pit slope failure is P_a=43/13,234=$3.25\cdot10^{-3}$. The total number of fatalities for the period 1982 to 2019 is D=145, therefore the life loss per failure is 0.11 (X=145/(31·43)=0.11).

The average cost of one slope failure was estimated based on the published open pit mine economic loss for Kennecott' Nevada Mine Division (the failure occurred in 1979), Smoky Canyon Phosphate Mine (the failure occurred in 1992), Boron (the failure occurred in 1998), and Bingham Canyon Copper Mine (the failure occurred in 2013). The cost of the failure includes losses due to having to close the mine, due to fatalities, due to loss of the equipment, and due to recovery operations. The failure cost varied between 10^5 and $6\cdot10^8$ (US\$2020) and averaged C=$1.59\cdot10^8$.

The locations on the risk charts for failures due to slope instability in open pit mining are presented in Figures 2 and 3.

Table 1. Summary of the calculations for the risks associated with the different public and civil engineering activities

Failure phenomenon	Time period	Years n	Total # of Failures F_t	Average annual # of failures F_a	Total # of structures or people, S	Average annual probability of failure, P_a with minimum and maximum	# of fatalities corresponding to one failure X with minimum and maximum values	Average cost associated with each failure C with minimum and maximum values (US\$2020)
Car accident fatality	1994-2018	25	973,698	38,948	$2.97\cdot10^8$	Average $1.31\cdot10^{-4}$ min $1.03\cdot10^{-4}$ max $1.57\cdot10^{-4}$	1	10^6
Fatal car accident	1994-2018	25	880,656	35,226	$2.43\cdot10^8$	Average $1.45\cdot10^{-4}$ min $1.09\cdot10^{-4}$ max $1.89\cdot10^{-4}$	1.67	Average $9.06\cdot10^6$ min $7.02\cdot10^6$ max $1.17\cdot10^7$
Cancer	1996-2019	24	13,680,806	$5.70\cdot10^5$	$3.02\cdot10^8$	Average $1.89\cdot10^{-3}$ min $1.84\cdot10^{-3}$ max $2.00\cdot10^{-3}$	1	Average $2.37\cdot10^5$ min $1.48\cdot10^5$ max $3.16\cdot10^5$
Heart Disease	2006-2018	13	8,054,019	$6.20\cdot10^5$	$3.13\cdot10^8$	Average $1.98\cdot10^{-3}$ min $1.91\cdot10^{-3}$ max $2.11\cdot10^{-3}$	1	-
Stroke	1999-2018	20	2,874,333	$1.44\cdot10^5$	$3.04\cdot10^8$	Average $4.73\cdot10^{-4}$ min $4.08\cdot10^{-4}$ max $6.00\cdot10^{-4}$	1	-
Heart Disease and Stroke	2006-2018	13	9,815,773	$7.55\cdot10^5$	$3.13\cdot10^8$	Average $2.41\cdot10^{-3}$ min $2.32\cdot10^{-3}$ max $2.58\cdot10^{-3}$	1	Average $4.95\cdot10^5$ min $4.33\cdot10^5$ max $5.20\cdot10^5$
General Aviation	2002-2018	17	4,642	273	$1.02\cdot10^7$	Average $2.68\cdot10^{-5}$ min $2.08\cdot10^{-5}$ max $3.79\cdot10^{-5}$	Average 1.76 min 1.21 max 2.59	Average $1.83\cdot10^7$ min $1.55\cdot10^7$ max $2.02\cdot10^7$
Commercial Aviation	1990-2018	29	61	2.10	$9.70\cdot10^6$	Average $2.17\cdot10^{-7}$ min 0 max $5.48\cdot10^{-7}$	Average 28.34 min 0 max 531	Average $3.68\cdot10^9$ min $1.11\cdot10^9$ max $2.83\cdot10^{10}$
Nuclear Reactors	1960-2019	61	4	0.066	76	Average $8.68\cdot10^{-4}$ min 0 max $1.32\cdot10^{-2}$	Average 0.75 min 0 max 3	Average $6.18\cdot10^8$ min $2.15\cdot10^7$ max $3.10\cdot10^9$
Bridge Scour	1970-2005	36	765	21.25	$5\cdot10^5$	Average $4.25\cdot10^{-5}$ min $2\cdot10^{-5}$ max $1.56\cdot10^{-4}$	Average 0.04 min 0 max 10	Average $1.45\cdot10^6$ min $1.20\cdot10^6$ max $1.80\cdot10^7$
Open Pit Slope Stability	1989-2019	31	1327	43	13,234	Average $3.25\cdot10^{-3}$ min $1.56\cdot10^{-3}$ max $4.73\cdot10^{-3}$	Average 0.11 min 0 max 9	Average $1.91\cdot10^6$ min 10^5 max $5.72\cdot10^8$
Earth Dams	1970-2020	51	234	4.68	79,709	Average $5.87\cdot10^{-5}$ min $1.25\cdot10^{-5}$ max $7.03\cdot10^{-4}$	Average 2.02 min 0 max 238	Average $1.82\cdot10^7$ min 10^5 max $1.37\cdot10^9$

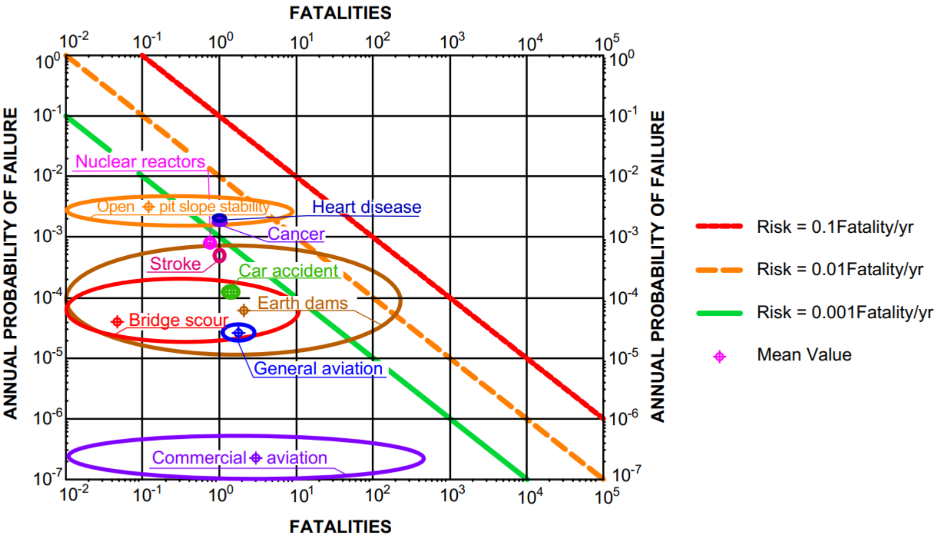

Figure 2 – Annual probability of failure vs. annual number of fatalities due to the failure

3.9 *Earth dams*

Based on the National Inventory of Dams (NID, 2020) maintained by U.S. Army Corps of Engineers, there are 91,457 dams in the US, 79,709 of which are earth dams. According to the 2017 Infrastructure Report Card, prepared by American Society of Civil Engineers (ASCE), about 17 % of the dams in the United States are identified as high-hazard potential dams (ASCE, 2020). The main causes of dam failure are overtopping, piping, and slope stability.

One of the most catastrophic earth dam failures was Canyon Lake Dam failure in South Dakota in 1972. This failure was due to overtopping and lead to 238 fatalities and US2020 $1,021.6 million of losses (ASDSO, 2020b).

This Dam Incident Database and other available resources were analyzed over a fifty-year period (1970-2020) for incident type and frequency, number of failures, fatalities, economic consequences, and other relevant parameters (NID, 2020; ASDSO, 2020a; ASDSO, 2020c).

The total number of earth dam failures in the US during that 50-year period was F_t=234. The corresponding number of fatalities was 472. The average annual number of failures is therefore F_a=4.68. The total number of earth dams in the country in 2020 is S=79,709. Therefore, the annual probability of earth dam failure is P_a=4.68/79,709=5.87·10^{-5} and the life loss connected to one failure is X=472/234=2.02. The average cost of one earth dam failure was estimated based on the Dam Incident Database (ASDSO, 2020a) and individual case histories published online (ASDSO, 2020c). The total cost of the 234 failures occurring between 1970 and 2020 was estimated at 4,254.16 million dollars. Therefore, the failure cost each time a failure occurs averages C=1.82·10^{7} US$2020.

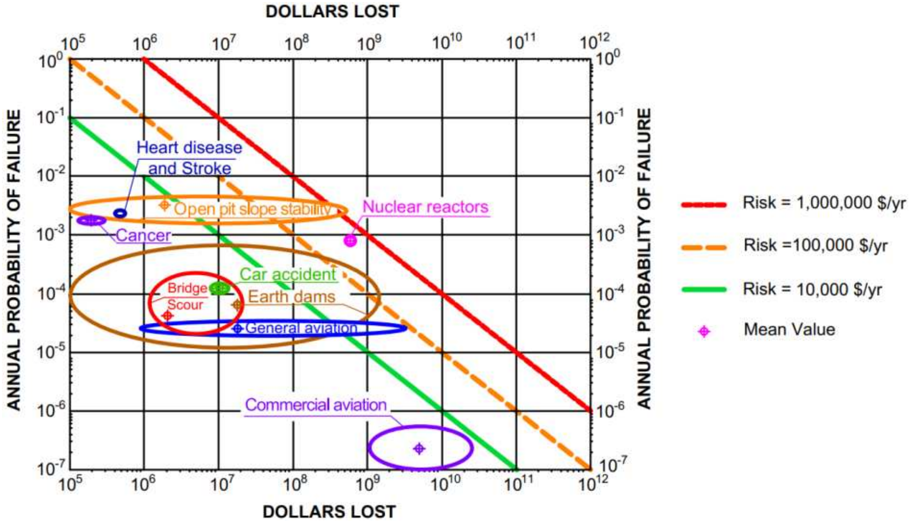

Figure 3 – Annual probability of failure vs. annual economic loss corresponding to the failure

4 FATALIITIES AND COST RISK CHARTS

Two risk charts for the United States were constructed based on the data presented in Table 1: the annual probability of failure vs. fatalities risk chart (Fig. 2) and the annual probability of failure vs. dollars loss risk chart (Fig. 3). Ellipses were used when there was a range of values associated with the probability of failure, the number of fatalities or the cost. The length of the horizontal and vertical axis of the ellipses indicate the range of the data. Note that the period of time over which the data is gathered varies from one activity to another (Table 2) and that those charts are prepared for the United States.

According to the ASCE Geo-Institute guidance document “Risk informed decisions in geotechnical engineering”, acceptable and tolerable risks are defined as follows. Acceptable risk is a state of risk which stakeholders are willing to accept. Action to further reduce such state of risk is usually not required unless reasonable measures are available at low cost in terms of money and time. Tolerable risk is a state of risk within a range that society can live with so as to secure certain net benefits. It is a range for a state of risk regarded as 'non-negligible', 'needing to be kept under review' and which 'must be reduced further if possible'.

On one hand, no fatality is acceptable, on the other hand, zero risk is not possible. The choice of an acceptable/tolerable risk is difficult because so many factors beyond geotechnical engineering enter into the decision including philosophy, politics, public awareness, and social sciences. Judging from the location of the ellipses on the two risk charts, it appears that the public tolerates a risk of 0.001 fatalities per year and 10,000 US dollars per year. The green, orange and red lines in the two charts correspond to low, medium and high risk levels (Table 2).

Table 2. Risk Levels for the United States

Risk Level	Risk ($/yr)	Risk (fatalities/yr)
Low	10,000	0.001
Medium	100,000	0.01
High	1,000,000	0.1

5 CONCLUSIONS

Risk is defined here as the probability of failure times the value of the consequence. Data associated with a set of activities is analyzed and presented in a fatality risk chart and in a cost risk chart. Risk values are $10,000/yr and 0.001 fatalities/yr seem to correspond to low risk and possibly tolerable risk. Most civil works are positioned in the tolerable risk zone with a few exceptions requiring attention. Engineers and other decision makers can estimate the location of their project on both risk charts and plan accordingly.

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