

NATURAL HAZARDS, RISK, AND THE RESILIENCE OF TRANSPORTATION INFRASTRUCTURE: AN EXAMPLE OF RISK-BASED GEOTECHNICAL ASSET MANAGEMENT

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ABSTRACT

The Colorado Department of Transportation (CDOT) has recently implemented a Risk-Based Transportation Asset Management Plan (RB TAMP) that incorporates geotechnical assets and hazards. CDOT's RB TAMP includes an ancillary wall structures program that includes all earth retaining structures, and a geohazards management program which is used to manage multiple hazards related to slopes, embankments, and roadway subgrade. The RB TAMP states multiple performance goals to be achieved, including safety, infrastructure condition, reliability, congestion, and maintenance, and the state will measure and report progress in these areas. Natural hazards, physical failures, external agency impacts and operational risks are risk types that present threats to CDOT's achievement of their goals. The way these risks act on assets to impact performance goals can be visualized in a cubic form, and this allows for recognition of how many elements of risk there are, for making explicit decisions on which risks to address and how, and for communicating these decisions to others. Risk analysis at CDOT includes both qualitative and quantitative approaches in accordance with data availability. The quantitative estimate of risk is expressed in terms of exposure cost for all assets, risk types and performance goals and then used by CDOT subject matter experts for project selection and planning. The estimated risk exposures are also categorized into Level of Risk grades that are used to concisely communicate risk levels to executive management and to compare the long-term performance risks between asset types under different funding scenarios in the RB TAMP.

1 INTRODUCTION

Geotechnical engineers have a long history of recognizing risk management as a part of their responsibilities. Casagrande wrote about calculated risk for highway embankment construction in his 1964 Terzaghi Lecture (1965) and many more authors have contributed to this discussion in the years since. Pierson et al. (1990) published important work for the transportation sector using risk as a basis for prioritizing decision on state highway rockfall sites. Those authors presented a rockfall hazard rating system (RHRS) that has since been adopted, and customized by many states, including Colorado, and for other uses as well. Though the word hazard is in the title, the characteristic assessed is one of risk (including likelihood and consequence), and the resulting decisions are risk-based.

The Colorado Department of Transportation (CDOT) has more recently implemented a risk-based transportation asset management plan which it uses to help make funding and project planning decisions. CDOT's plan is consistent with the requirements of MAP-21 and the FAST federal authorizations that require all states to develop such a plan. CDOT's plan addresses risks related to geohazards such as rockfall, and geotechnical assets such as slopes and retaining walls, and are thus related to the work that evolved from Pierson (1990). This is because the potential consequence of a geohazard or poor performance of a geotechnical asset can threaten CDOT's plan to achieve its mission to "provide the best multi-modal transportation system for Colorado that most effectively and safely moves people, goods, and information".

CDOT is pioneering the way geohazards are being measured with respect to risk and the way risks from geohazards are compared directly with risks from other assets and used to prioritize spending and plan projects. Risk is a word and concept that can mean different things and be used in different ways, and CDOT's RB TAMP considers risk in a more expanded way than Pierson (1990). CDOT's RB TAMP includes an ancillary wall structures program that includes all earth retaining structures, and a geohazards management program which is used to manage geohazards related to slopes, embankments, and roadway subgrade. The RB TAMP explicitly states multiple performance goals and addresses risk types that present threats to CDOT's successful achievement of established targets for their goals. The way these multiple risks act on multiple assets to impact multiple performance goals can be visualized in a cubic form, called a risk cube. The visualization allows for recognition of how many elements of risk there are, for making explicit decisions on which risks to address and how, and for communicating these decisions to others, which CDOT has done.

2 BACKGROUND

2.1 HAZARDS AND ASSETS

The CDOT RB-TAMP recognizes 11 asset groups (pavements, bridges, maintenance [traffic and safety devices], buildings, intelligent transportation systems [ITS], fleet/road equipment, tunnels, culverts, geohazards, retaining walls, and traffic signals). These are things that CDOT has purchased or built (with plans and specifications). It is a little different with respect to the geohazard asset group, but CDOT maintains the right of way and has built a highway corridor that is underlain by subgrade and bounded by slopes. The vast majority of the subgrade miles and the slopes are unaffested, but the rest of them are where geohazards are realized, so effectively CDOT owns the hazards and corresponding threats. The geohazards recognized by CDOT in this way are specifically defined as follows.

Apart from being commonly used to protect the ballast layer against subgrade attrition, sub-ballasts are mainly designed to act as a stress dissipation layer (commonly called a capping layer). If ever used as a filtration layer, the design criteria currently used in the industry to select the sub-ballast is still based on the guidelines primarily based on the monotonic seepage loading common in embankment dams. In rail track environments, the loading system is cyclic and the mechanisms of filtration, interface behaviour, and time dependent changes of the drainage and filtration properties that occur within the filter medium require further understanding. Under the influence of cyclic loading, sub-ballast filtration parameters that are important in conventional rail track design have to be identified and studied in detail.

- debris flows
- drainage/seepage features
- embankment distress
- landslides
- rockfall sites
- rockslides
- sinkholes
- subgrade distress

It is possible to look at the 8 geohazards independently and to manage them directly. It is also possible to condense them into three categories of slopes, embankments and subgrade, as is useful for some of the discussion in this paper. When grouped in this way, it is more intuitive that slopes, embankments and subgrade are assets much in the same way as bridges and pavement. They are not just important; they are mandatory components of a highway that forms a transportation corridor. Thus, slopes, embankments and subgrade could be added to CDOT's list of 11 asset groups (in lieu of geohazards). These 3 asset types, along with retaining walls (already in the CDOT list) have elsewhere been identified as independent geotechnical assets (Anderson, 2016) because they are comprised of soil and rock or have performance governed largely by soil or rock, and they are independent of other asset classes typically considered by highway transportation agencies. In summary, CDOT has a RB TAMP to manage several different assets with respect to risk, and four of them are geotechnical.

2.2 PERFORMANCE GOAL

Performance goals have been set at the federal level in highway transportation through the MAP-21 and FAST act legislation and these goals have been adopted by states in a context that is meaningful to the state. CDOT has the following primary goals set by state policy directive and identified in their RB-TAMP:

1. Safety – Reduce traffic fatalities and serious injuries and work toward zero deaths for all users.
2. Infrastructure Condition – Preserve the transportation infrastructure condition to ensure safety and mobility at a least life-cycle cost.
3. System Performance – Improve system reliability and reduce congestion, primarily through operational improvements and secondarily through the addition of capacity.
4. Maintenance – Annually maintain CDOT's roadways and facilities to minimize the need for replacement or rehabilitation.

CDOT has other goals beyond these, such as freight movement and environmental sustainability that also align with MAP-21. CDOT treats these as "Planning Principles" and in that way incorporates them with the achievement of other goals. In summary, CDOT is now very explicit in trying to achieve targets for multiple performance goals simultaneously.

Other agencies are too. The path to doing this includes management of multiple assets and making decisions based on opportunities and threats, which is where risk-based management is engaged.

2.3 SOURCE OF RISK

Risk comes from multiple sources and there are many ways of categorizing risk, but for the purposes here a categorization made by the American Association of State Highway and Transportation Officials (AASHTO) is particularly useful (AASHTO, 2011). AASHTO defines four types of risk that are all relevant for geotechnical assets:

1. Natural hazards
2. External agency impacts
3. Physical failure
4. Operational risk

The risk from natural hazards can be viewed as something originating beyond the ability to control and it can be mitigated primarily by actions that prepare for it and prepare for recovery from it. In other words, the risk can be reduced by actions that reduce its consequence and not its likelihood. Some examples are extreme events, such as earthquake hazards, and large, rare floods, as well as regionally pervasive geohazards such as swelling soil. Landslides such as the tragic 2014 landslide in Oso Washington that took 43 lives and buried SR 530 are another example of a natural hazard. An important recognition of this is that natural hazards will still occur and pose some level of risk, even with the best application of risk-based asset management. Geohazards are a subset of natural hazards.

In contrast to the natural hazard risk type, the physical failure type of risk is that which happens through an ongoing process of deterioration, much like pavement or bridge decks deteriorate (e.g. Galehouse et al., 2003). The shape of a deterioration function for geotechnical assets is not well known because these assets have not had much study in this regard. Experience does show, however, that many geotechnical assets deteriorate and do so at an increasing rate if actions are not taken to preserve them. Examples are the maintenance of surface and subsurface drainage on slopes or earth retaining structures, the maintenance of vegetation and riprap, and facing materials, and the maintenance of rock slopes and rockfall mitigation equipment through scaling and repair of improvements. These preservation actions and others serve to reduce the consequence and/or likelihood of the physical failure risks and their efficacy in doing so depends in part on their timing, which is also within control of CDOT. This risk type is, therefore, very effectively addressed with transportation asset management practices.

The operational risk type and external agency impacts risk type apply differently and are not as well managed by using transportation asset management principles as they are addressed using other means. Operational risk is the risk related to business decisions and whether the owner agency makes good or poor decisions related to its ability to get the right people delivering the right project at the right time and to accidents from the public use of the system. External agency impacts are risks related to what is delivered to the agency. These include the quality or price variance of materials and design or construction services purchased. These risks are managed to an acceptable level by business practices, for example implementing quality assurance to manage external impacts, and business planning, personnel practices, and training/education for operational risk.

2.4 RISK CUBE

Each asset group (walls, slopes, etc.) can be viewed as a path through which each risk type acts to threaten achievement of the performance goals. Risk of any type and consequence (which can be measured uniquely in the context of each goal) can be mitigated by taking actions that impact the asset (path). Thus, CDOT owns an element of risk related to each combination of asset, goal and risk type, and it can be mitigated by actions on the assets. Considering the assets, goals, and risk types defined by CDOT and summarized in the previous sections, this elemental risk matrix is a 3-D form that can be viewed as a "risk cube" as shown in Figure 1 (Anderson, 2016).

A way to look at this figure is to view each element as a place holder for the calculated or estimated risk of a specific type acting through a given asset type and having a consequence related to a specific performance goal. Thus, this cube shows 64 elements of risk. The magnitude of risk in some of these elements will be far greater than in others and many elements, rows, columns, or even planes of risk elements can be recognized as secondary based on inspection or preliminary analysis. For other elements of risk, it will be important to make more careful assessments or analysis of risk, and to consider actions and the desired timing of actions that will reduce those risks.

As demonstrated in the following sections, the risk cube helps to communicate what risks are high, what are being addressed by certain actions, and what risks remain. The risk cube visualization applies at any scale: individual asset, corridor segment, corridor, or highway system. Retaining walls are considered by CDOT as individual assets, and for the geohazards program all geohazards are lumped together for a segment of a corridor. As can be imagined, the risk mitigation strategies envisioned for an element of risk will depend on the scale being considered.

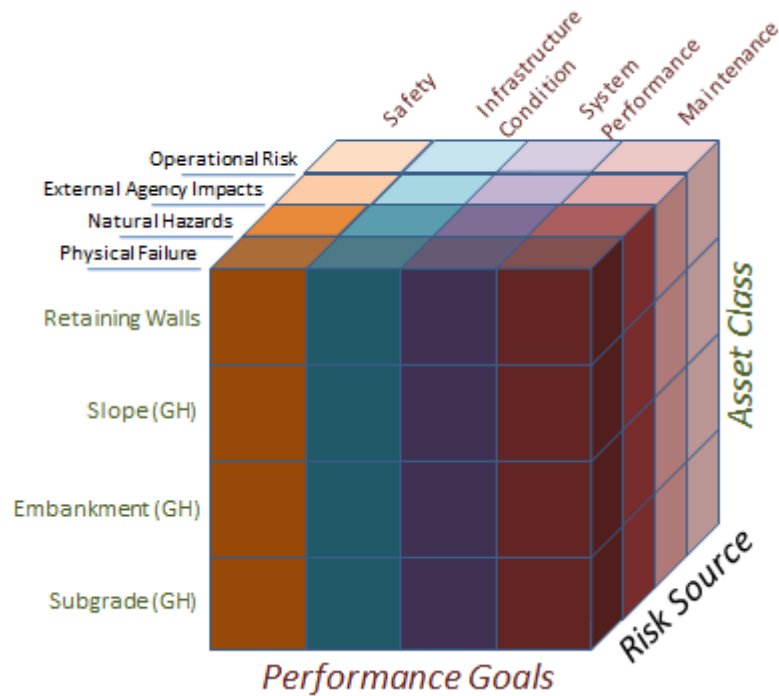


Figure 1: Elements of a “risk cube”. GH indicates asset is considered only through impact of geohazard in CDOT’s RB TAMP

3 GEOTECHNICAL RISK CONSIDERATION BY CDOT

Risk-based management of geotechnical assets (geohazards and retaining walls) involves evaluating a range in potential consequences that align with pre-established department performance goals (in parentheses) as follows:

- condition deterioration to the specific asset (infrastructure condition and maintenance);
- public safety (safety);
- traveler delay, congestion, and mobility impacts (system performance);
- department maintenance expenses for asset repair (maintenance);
- environmental resource damage (other);
- economic loss (system performance); and
- private property damage (system performance and economic vitality).

During an initial phase of risk assessment, retaining wall assets were determined to have greater impacts to mobility and asset (infrastructure) condition than to other goals. These impacts could be evaluated based on traveler delay and department maintenance expenses, respectively. By using maintenance expense as a measure of consequence for the condition goals, it is effectively rolled into these goals and not considered separately (as in bullet four, above). For other geotechnical assets, similar conclusions were made, and in addition, it was possible to assess the risk to public safety. Other performance areas such as environmental resource damage could be evaluated. However, these impacts were generally minor and found to be duplicative to other performance areas, or not seen as reliable for incorporation into the asset management plans.

3.1 RETAINING WALL MANAGEMENT

The retaining wall management program (CDOT, 2016) consists of over 3,000 walls and is based on the National Bridge Inventory (NBI) ratings and the element level rating required for all bridges. The NBI has been established to help ensure safety by tracking the condition of various visible elements through time. The idea is that a bridge element which is deteriorating will be detected and can be addressed before there is a safety consequence. Because these data are available, they are now being used for more than safety: they are being used for bridge performance management, and that is the same approach that CDOT’s risk-based wall management program is using.

Though CDOT's wall management program is an integral part of their RB TAMP, it addresses only two elements of geotechnical risk, as shown in Figure 2. Ten elements of risk in the upper plane for retaining walls are not addressed by the RB TAMP. Note that Figure 2 uses CDOT terminology for performance goals: safety, maintenance and mobility. Recognition that only two of twelve possible risk elements are considered by the RB TAMP is important. CDOT can consider if the other elements are significant and if they are managed in other ways, or if they should be incorporated in the RB TAMP.

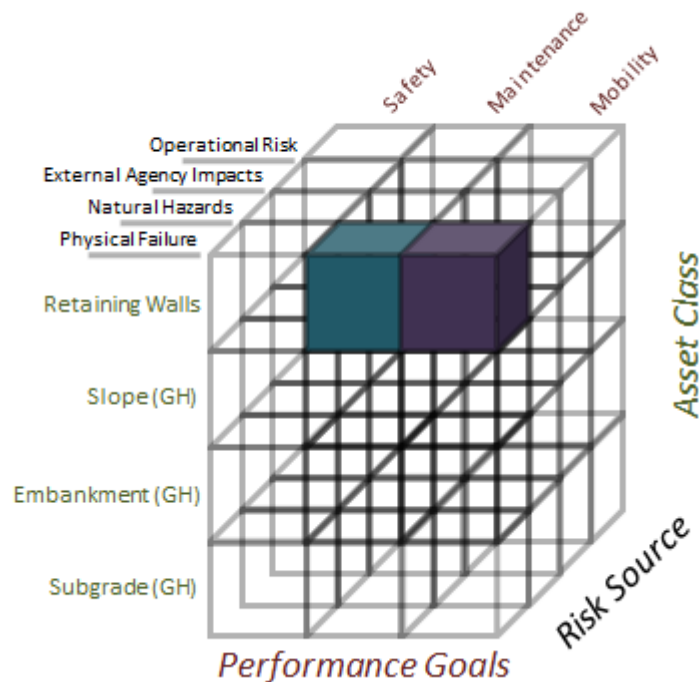


Figure 2: Elements of risk in the CDOT wall management plan

CDOT started with an initial phase of risk assessment to establish a priority for doing more labor and data intensive assessments of all walls. The Tier 1 assessment did not distinguish the two risk cells shown in Figure 2; however, the second tier of assessment, which is still going on, does. The Tier 2 assessment incorporates measurable data collected during inspections of wall and structure element conditions to estimate the risk exposure, develop performance goals and metrics, and support decisions for long-range planning. The measurable parameters used in the maintenance and mobility risk calculations are outlined in the following sections.

3.2 MAINTENANCE GOAL RISK

Each wall asset is composed of elements that are defined as visible features such as facing, coping, and drainage components. The maintenance risk exposure is determined based on a weighted repair cost that considers the quantity and category of these structure elements (primary or secondary) and the field assessed condition state of the element. The parameters used in the calculation are shown in Table 1. Primary elements, which are structural in nature, are assumed to have a greater priority for repair than secondary elements, which tend to be cosmetic or ancillary. Structural elements are thus weighted more heavily in the determination of risk cost due to the potential for the financial consequences to be recognized by CDOT for these elements over the wall life cycle. Similarly, defects in elements categorized in good or fair condition typically have a lower priority for repairs than those in severe condition and are, accordingly, weighted less heavily. The unit costs to repair defects represent consequence in the determination of maintenance risk cost. The element category and the condition state score are used as surrogates for likelihood and represent the probability of repairs being made and maintenance costs being incurred. The likelihood (or probability) estimates presented in Table 2 for various element categories and condition states are based on input from CDOT and consultant staff and reflect past experience and professional judgment. These can be interpreted as annual probabilities. The resulting maintenance risk exposure is calculated as the sum of the product of each element cost (unit cost x quantity) and likelihood that a direct maintenance cost for that element would be incurred (values from Table 2 based on element type and condition state for that element).

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Table 1: Retaining wall maintenance risk calculation parameters

Performance Goal	Factor	Parameter
Maintenance		
	Consequence	Quantity of Elements
		*Unit Costs
	Likelihood	Condition State
		Element Type
		Element Category (primary or secondary)

* Data compiled based on inspector experience and with CDOT input

Table 2: Probability Values for Risk Exposure Calculation

Likelihood of Incurring Maintenance Cost		
Condition State	Primary Elements	Secondary Elements
1 (best)	0%	0%
2	11%	7%
3	59%	37%
4 (worst)	98%	66%

3.3 MOBILITY GOAL RISK

User costs represent an estimate of the consequence to mobility in the determination of mobility risk. User costs are indirect costs for closure or delay and they are calculated for both the roadway in front and the roadway carried, as applicable in scenarios of tiered roadways. The parameters used to calculate user cost are shown in Table 3. Geometric parameters such as height and closeness to the road indicate how big the impact will be to the road and the average annual daily traffic (AADT) reflects how many users experience that impact.

The likelihood of an event is determined by the condition of the wall as dictated by the lowest inspection score received for the items of main structure condition, foundation condition, or scour critical condition. These items are adapted from the NBI. The state has been collecting this type of information on bridges for many years, but using these condition scores to predict likelihood of an impact to the mobility performance goal is a new idea. The likelihood of risk exposure based on the condition score is based on input from CDOT and contractor inspection staff and reflects experience and professional judgment, and is presented in Table 4.

Based on this process, the final mobility risk calculation, representing the product of consequence and likelihood, can be calculated as follows:

$$\text{User Costs} = \frac{\text{Delay Time} \times (\text{AADT Actual} - \text{AADT Delay})}{3600 \times 24} \times \text{User Value} \times \text{Occupancy Rate}$$

$$\text{Mobility Risk Exposure} = \text{User Costs} \times \text{Wall Condition}$$

Table 3: Retaining wall mobility risk calculation parameters

Performance Goal	Factor	Parameter
Mobility	Consequence	Avg. Wall Height
		Avg. Distance from Road in Front
		Avg. Distance from Road Carried
		AADT
		^Delay Time, 2 hours
		*User Value, \$30.50
		*Occupancy Rate, 1.67
		*ADT Delay, 33% of Actual ADT
		Likelihood
	Foundation Condition	
	Scour Critical Condition	

^Assumed value based on likely time of delay from an urgent adverse event, similar to delay associated with over-height bridge strikes.

*Per AASHTO 2010.

4 ESTIMATED EXPERIENCE-BASED CORRELATION OF WALL ITEM CONDITION AND LIKELIHOOD OF RISK EXPOSURE

Through these approaches, a financial risk exposure is calculated for both shaded cells shown in Figure 2, and these individual risk costs are summed to arrive at a total risk exposure for each wall. As the sum of estimated risk exposures for retaining walls are determined, CDOT can evaluate the data for deterioration trends related to wall and element types, age, and location. Further, CDOT anticipates recognizing cost savings through the bundling of wall rehabilitation projects to address similar performance issues, such as repair of common drainage and wall facing systems for multiple walls. Additionally, CDOT can better evaluate the long-term performance of decisions made during design, such as the trade off in asset management performance between different wall systems.

4.1 GEOHAZARD MANAGEMENT PLAN (GMP)

The CDOT Geohazard Management Plan (GMP) consists of over 1,600 highway segments with an identified threat that has been documented through a prior geologic event. About half of these sites consist of rockfall locations previously identified by the CDOT Rockfall Hazard Rating System and the remaining locations consist of geohazards such as unstable soil and rock slopes or subgrades. The geohazards program comprises the three remaining independent geotechnical assets: embankments, slopes, and subgrades, and calculates risk for CDOT’s three performance goals, as defined for walls. For each performance goal the risk estimate is based on the associated threat such as traveler injury from a geohazard event, highway closure, or direct maintenance costs to the department. The condition of the geohazard asset is determined based on the number of recorded events, which is then converted to an annual probability that there would be a consequence to one of the performance areas. For example, a rockfall geohazard location may experience three events in a year; however, not all events will result in an impact to the traveler safety, mobility, or maintenance direct expenses. CDOT subject matter expertise was used to estimate the annual probability for a performance impact based on the number of events. Further, the estimation of safety risk exposure includes a vulnerability value to account for the likelihood that not all accidents attributed to a geohazard location will result in an injury.

Different levels of consequence are assigned to each geohazard based on historical ranges of impact. Estimated costs associated with each level of safety and mobility consequence were then assigned based on internal department economic studies that are being developed for broad planning purposes. The cost consequence associated with threats to maintenance was based on the judgment of the ability of maintenance budgets to accommodate unplanned expenses. As

this is a new process that relies on historical and current data as well as evolving estimates of consequence, the input values may change as the plan evolves. However, in the interest of initiating risk management CDOT is moving forward with a plan that can be adjusted as the confidence in data and means improves. The process for the assessment of geohazard risk exposure is presented in Figure 3.

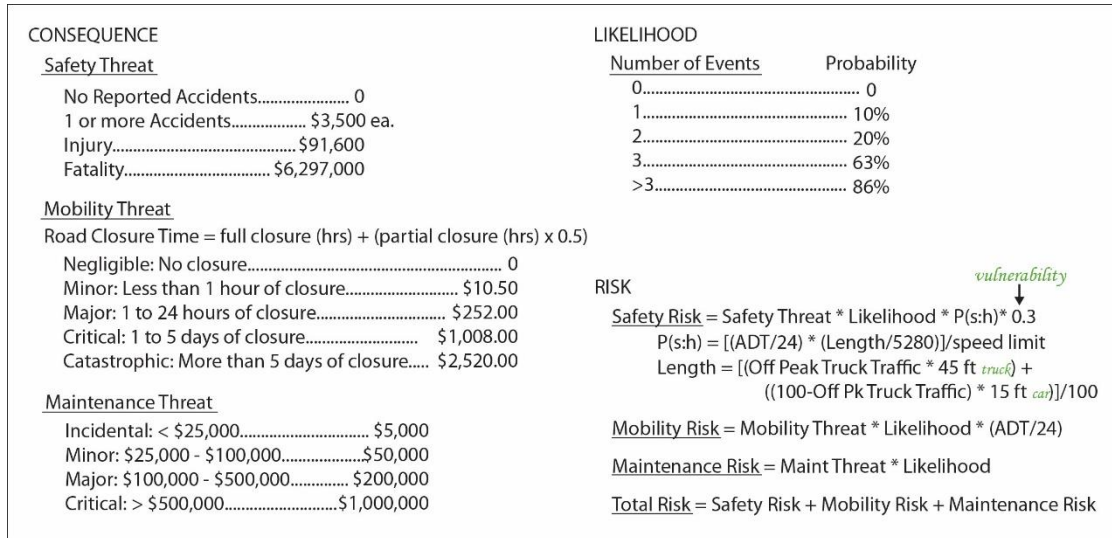


Figure 3: Calculation of Total Annual Geohazard Risk Exposure

CDOT’s GMP is focused on physical failure as a risk type, though it also considers natural hazards because events tied to natural hazards are not distinguished in the data. In other words, there has been no attempt to retroactively assign a risk type to the 1600 highway segments that have been identified. The inclusion of two risk sources for the GMP differs from the wall program, which considers only physical failure. Thus, the calculated risk exposure from Figure 3 represents the both the natural hazard and physical failure elements of risk and the elements of natural hazard risk type are included with those of the physical failure type in Figure 4 because of their implicit role in the past data collection and valuation. A possible future activity for CDOT is to separate these risk types. The data being collected now as part of this program will be helpful for doing so.

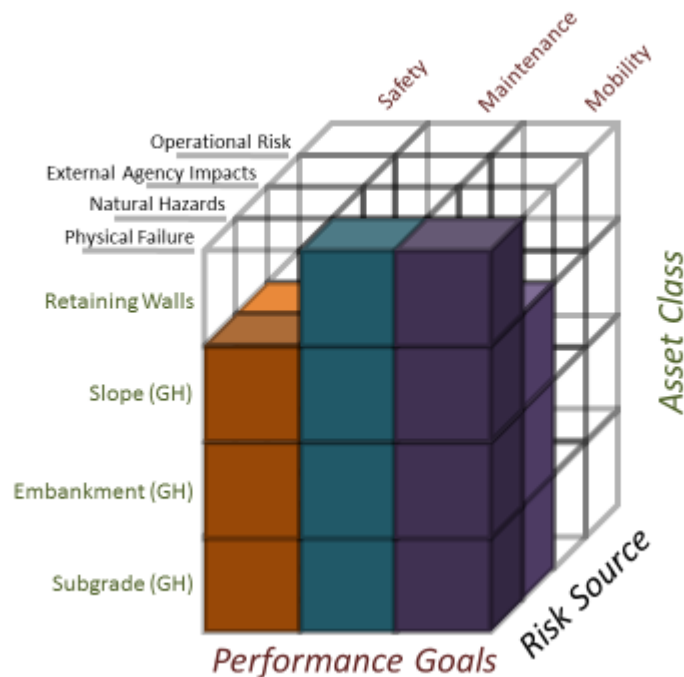


Figure 4: Elements of risk in the CDOT wall and geohazard management plans.

While the historical distinction between physical failure and natural hazards has not routinely occurred some interesting observations are possible. For one, expectations for performance levels and funding sources after extreme event natural hazards are different. Damage is expected when extreme events have a recurrence interval greater than the design life of a structure (including obsolete structures), for example, and federal Emergency Relief funds can be available after a government declaration of disaster. Further, recent work by CDOT has estimated the broader economic consequences from both natural hazards and physical failure of geohazards. Through this work, CDOT is able to demonstrate to external stakeholders the benefits that CDOT delivers through their response to natural hazards that originate from outside the CDOT right-of-way. In the future, it may be possible to obtain additional funding contributions from stakeholders should there be a strong desire to improve the performance of a corridor exposed to natural hazards.

Additionally, CDOT and other state transportation departments frequently assume the responsibility of both risk sources because they are most capable of quickly responding with resources for repair and construction. As an example, the U.S. Forest Service or a state/federal land management agency does not have missions that involve maintaining the economic vitality of a region through good performance of transportation corridors. Should a hazard originate from property managed by these other agencies, they are typically not able to respond in a manner that would rapidly restore the affected transportation corridor. If a distinction between risk types is made in the future, it may help CDOT quantify this value.

The total risk exposure calculation (Figure 3) allows CDOT to develop projects and maintenance plans following a risk management approach that is in alignment with the department performance goals. Additionally, when viewing the risk exposure by highway segment in a geographic information system (GIS) or other mapping environment, it is possible to identify geographic concentrations of risk. This allows CDOT to define management corridors that can be prioritized for mitigation based on the potential for greater levels of risk reduction in a concentrated area. This approach results in a more rapid and measureable improvement in system performance because an entire corridor is improved in a shorter duration, versus dispersing projects among several corridors without significant reductions in risk in those corridors. In fact, this is a key anticipated outcome of risk-based asset management.

Additionally, the benefit of routine maintenance activities is able to be better qualified in terms of multiple performance goals rather than treated as an isolated nuisance cost. For example, CDOT recently mitigated a rockslide feature through a planned removal project for a relatively direct low cost. A photograph of the site immediately following the slope hazard reduction work is presented in Figure 5 and illustrates the potential threat to safety, mobility, and condition of the system (the “maintenance” goal). By proactively performing this work, CDOT was able to control the safety threat at the site while also minimizing the consequences to mobility and department maintenance expenses. When the cost of the mitigation is compared with the reductions in risk exposure in terms of safety, mobility, and department maintenance expenses, actions like this can demonstrate a favorable benefit:cost ratio. In other words, and using the risk cube for visualization, the action, timed as it was, mitigated risk in the three elements that are the intersection of the geohazards on slopes (Slope (GH)) plane and the physical failure plane, which is the risk source here.



Figure 5: Rock Slope Risk Exposure Reduction on US 24 near Minturn, Colorado.

4.3 OTHER RISK ELEMENTS

Despite the very proactive approach taken to manage risk by CDOT, it can be seen from Figure 4 that there are many elements of risk not addressed by the wall and geohazard programs. The risk cube helps communicate this point so that people coming from all perspectives can see what other risks are present. CDOT can then make informed decisions to accept the risk in other elements, as secondary, low-level risks or they can complete other programs to mitigate them. For example, CDOT's asset management plan does not address operational risk and external agency risk because these are mitigated by business practices, which CDOT does undertake and continuously evaluates in other processes.

4.4 LEVEL OF RISK

The measurement and reporting of asset risk to executive and planning professionals in a transportation department needs to be conveyed in a simplified manner. For this to occur within CDOT, the concept of a level of risk (LOR) grade was established to communicate the qualitative categorization of the risk exposure. The LOR concept was modified based on other related categorical measures, such as level of service, which are commonly used within a DOT to communicate performance to executives and public.

For wall and geotechnical assets, a monetized risk exposure was estimated for each of the performance goals, such as safety, mobility, and asset condition (planes in the risk cube). The individual risk costs are then aggregated to define the LOR as follows.

- A – less than \$1,000 risk exposure
- B – \$1,000 to \$5,000 risk exposure
- C – \$5,000 to \$50,000 risk exposure
- D – \$50,000 to \$100,000 risk exposure
- F – greater than \$100,000 risk exposure

The LOR category values were selected based on the assumed tolerance for differing economic consequence levels for the annual performance of walls and geohazard assets. The underlying exposure in the LOR categories is intended to be an estimate of the economic consequence, considering both direct and indirect costs, associated with ownership and maintenance of the assets. Initially, the categories for the GMP were established on the basis of a relative, non-monetized risk score, similar to the Tier 1 process used for the wall asset group. However, the goal of an asset management plan to develop financial and investment strategies that are measurable and the use of the estimated risk cost enables this to occur. Further, there is a real cost for delaying risk management as demonstrated by an internal study commissioned by CDOT on the economic consequences from geologic hazard events within right-of-way (Vessely et al., 2017). Vesseley et al. provide an estimate of the direct and indirect costs associated with ownership and maintenance of the GMP asset group and also provide a means to compare actual economic impacts with the total estimated risk exposure in the GMP. As a result, the emergence of these CDOT risk based plans are supported by executive management based on the goal to quickly achieve the benefits from risk reduction rather than waiting on others to develop a process.

The comparison of LOR between walls and geohazards has not yet occurred in the asset management process at CDOT, but the option does exist. A productive future process will be for the wall and geohazard asset groups to overlay LOR values for the respective assets and identify locations where combined investment strategies will demonstrate improvement to both asset groups, resulting in a more favorable cost to benefit ratio. While LOR is used for measurement and reporting to department executives, the underlying data are available to subject matter experts for project planning and development. For example, if the department has a mandate to develop projects that improve traveler safety or mobility, the data can be de-aggregated consider only those goals. This would eventually allow the department to examine the risk exposure associated with each individual cell within the risk cube.

5 CONCLUSIONS AND RECOMMENDATIONS

The management of risk in geotechnical engineering is well-established. These risk-based concepts and processes can be adapted within the transportation sector for the management of threats originating from constructed assets and natural hazards, as demonstrated by the inclusion of retaining walls, slopes, embankments, and roadway subgrade in a risk-based transportation asset management plan.

CDOT's RB TAMP considers natural hazard and physical failure risk types for geohazards and the physical failure risk type for walls. Geohazard risk calculations include some component of deterioration (physical failure) and some

component of resilience to natural hazards. Bridge management approaches, and therefore wall management approaches that mimic them, are based on observing things deteriorate, not ensuring resilience to extreme events, so the wall management program does not address risks from natural hazards. The elements of risk that are not captured here are omitted explicitly because either they were judged to be a second or third order contribution to risk, and not where management should be directed, or they are addressed by programs other than RB-AMP. The cubic form of the “risk cube” helps convey this clearly.

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