MĀLAMA I KE KAI ‘O WAIPI‘O, *et al.* vs., MITCHELL D. ROTH, *et al.*
CIVIL NO. 3CCV-22-0000106

Plaintiffs' Exhibit C

From: Pause, Stephen (Steve) <Steve.Pause@hawaiicounty.gov>
Sent: Wednesday, March 9, 2022 10:43 AM
To: Chris Yuen <chrisyuenz@hotmail.com>; Marsters, Janice <Janice.Marsters@hartcrowser.com>
Cc: Kurata, James K <james.k.kurata@hawaii.gov>; Chang, Carty S <Carty.s.chang@hawaii.gov>; Trisler, Dan <Dan.Trisler@hartcrowser.com>; Rodenhurst, Ikaika <Ikaika.Rodenhurst@hawaiicounty.gov>; Braman, Eva <Eva.Braman@hawaiicounty.gov>; Kanae-Kane, Sherise <Sherise.Kanae-Kane@hawaiicounty.gov>; Johnasen, Cyrus <Cyrus.Johnasen@hawaiicounty.gov>; Schlueter, Dalilah <Dalilah.Schlueter@hawaiicounty.gov>; Strance, Elizabeth <Elizabeth.Strance@hawaiicounty.gov>; Roth, Mitch D <MitchD.Roth@hawaiicounty.gov>
Subject: RE: Introduction between Board Member Yuen and Hart Crowser

Aloha Mr. Yuen,

Mahalo for your comments.

The County of Hawaii contracted with Hart Crowzer to complete the geotechnical engineering evaluation for Waipi'o Valley Road. Based on the results of their work, County DPW recommended to Mayor Roth that to protect the public from the possibility of injury or loss of life, the roadway should be closed to pedestrians and roadway use be limited to reduce risk and limit wear and tear on the road. DPW also indicated that there would be rainfall events that resulted in complete roadway closing at certain times.

We have confirmed with Hart Crowzer, to whom you reached out directly (without the County being a part of those discussions) that their analyses, methodology, and conclusions are all appropriate. The County DPW stands by Hart Crowzer's findings and our recommendation that the path selected is the most suitable way forward to ensure the protection the public's health, wealth, and safe. We do take seriously the impacts to the community, however, protecting the public is our first concern.

As we continue advancing with further investigations and development of mitigation measures and priorities, the County DPW looks forward to the input of all stakeholders so that we may select and implement remedies that will ensure long-term, safe passage to the community and all of those who may access the Waipi'o Valley.

Lastly, I request that you refrain further from contacting Hart Crowzer directly and forward correspondence to me, at County DPW. It is not appropriate for you in your position to work directly with a consultant under contract to the County DPW. I hope you can appreciate this.

Mahalo. ~steve

Steve Pause
County of Hawai'i
Department of Public Works
O (808) 961-8321

MĀLAMA I KE KAI ‘O WAIPI‘O, *et al.* vs., MITCHELL D. ROTH, *et al.*
CIVIL NO. 3CCV-22-0000106

Plaintiffs' Exhibit B

From: Chris Yuen
Sent: Tuesday, March 1, 2022 12:28 PM
To: Steve.Pause@hawaiicounty.gov <Steve.Pause@hawaiicounty.gov>
Subject: Waipi'o Road risk assessment

Aloha Mr. Pause: Thank you very much for speaking with me earlier this morning. I am sure you are extremely busy and I appreciate how much time you took to talk with me.

I asked you about your interpretation of the key numbers in the Hart Crowser geotechnical study: the risk of death for pedestrians walking the Waipi'o Valley Road--1/18,000, and the risk of death for motorists--1/170,000. The study does not explicitly say what that means.

You told me that it was per user per day. Thus, for pedestrians, it means you would expect one pedestrian to be killed by a rockfall per 18,000 pedestrian trips, and one motor vehicle occupant to be killed by a rockfall per 170,000 car trips. We went through this in detail using these examples.

This is one possible interpretation of the report and I absolutely agree that the County could not allow pedestrian travel if you would expect one death from rockfalls per 18,000 pedestrian trips.

I do not think the report means this, however. First, it is extremely implausible. The report is based on 137 pedestrian trips per day, or 50,005/yr. If this estimate of one per 18,000 pedestrian trips were correct, we would expect to see about 2.8 pedestrian deaths per year from rockfalls. I have never heard of any. We discussed this during the call. Second, because the study estimates 6 rockfalls per year, to cause 2.8 deaths/yr., almost half the rockfalls would have to hit someone. That is absurd. If the study means what you've interpreted it to mean, something is deeply wrong with the study. I could go through the same analysis for the risk to vehicles.

I don't understand exactly what Hart Crowser did to come up with their estimate. I follow the arithmetic but I don't understand why they combined two methods. I note, however, that in the context of their report, risk appears to be measured assuming an exposure of **one person per day per year**. For example, in Table 5, the risk of death from auto accidents is 1/23,000, which is roughly the per capita death rate in Australia from auto accidents, and they would assume that a person gets in a car every day. The figures for other activities also make sense if the exposure is one person per day for a year.

If the estimate does mean one death per 18,000 persons hiking the trail every day for a year, it is 1/365th of your interpretation. Or put another way, it is one death per 6.57 million pedestrian trips.

I've done my own estimate using the Hart Crowser input numbers and I get about 1 rockfall death per 5 million pedestrian trips.

The report does say that the risk to pedestrians is greater than "acceptable." It says this in the context of recommending mitigation, however. It does not recommend stopping pedestrians or vehicles. In the end, what is "acceptable" is a community decision based on both the risk and the reward. I think that the value of walking into Waipi'o is worth a 1 in 5million to 1 in 6.57 million chance of being killed by a falling rock on any one trip. I think most people would agree. Perhaps you would agree too. To put it in context, it is less than the risk of dying in a car accident on a trip between Honoka'a and the Waipi'o lookout.

You shouldn't rely on anything I am saying, but I hope that I've raised enough questions that you seek clarification from Hart Crowser about what they meant.

If what I am saying is correct, the advice from DPW to the Mayor to close the road except for vehicular travel for residents and farmers was based on an extreme over-estimate of the actual risk. I listened to the recent zoom meeting and read the Mayor's proclamation. The report's conclusions about rockfall hazard were the reason for this emergency measure. The Mayor and DPW repeatedly said that this is not something the County wanted to do.

I am not minimizing the hazards of the road itself, apart from rockfalls. But these have existed for a long time and do not warrant emergency action, nor were they the stated basis. These hazards need traffic management. Pedestrians are not the main problem. And people are walking on roads with some rockfall hazard all over the island.

There are also hazards from big landslides. These usually happen during or after heavy rains. Little recreational use occurs at those times.

You asked about my "endgame." If the decision to close the road was based on an extreme overestimate of the actual risk, this emergency action was unwarranted. I've been in government for years. I know it is extremely unpleasant to undo a decision. But it is a mark of good government to revise policies in light of new information. It is a mark of bad government to just keep the same policies but give a new reason. I am hoping that the county can change this decision gracefully.

I am a member of the state BLNR but I am writing this in my personal capacity. I was also county planning director from 2000 to 2008. --Chris Yuen

MĀLAMA I KE KAI ‘O WAIPI‘O, *et al.* vs., MITCHELL D. ROTH, *et al.*
CIVIL NO. 3CCV-22-0000106

Plaintiffs' Exhibit D

From: Chris Yuen <chrisyuenz@hotmail.com>
Sent: Thursday, March 3, 2022 4:52 PM
To: Chang, Carty S <carty.s.chang@hawaii.gov>
Subject: [EXTERNAL] Re: rockfalls

Hi Carty, thank you very much for contacting the consultant. I also thank him for the explanation. With all due respect, however, these numbers greatly over-state the risk (by two orders of magnitude) if you use their numbers and follow established techniques. Assumptions about changing conditions do not affect the risk analysis, which is based entirely on a few parameters. **Please forward this email to the consultant for his review and consideration. This is really for their review and response, not yours.**

I hope Hart Crowser's engineers and I can consider this together objectively. If I am wrong, I would certainly like to be corrected. If the consultant is wrong, I am sure he would like to make corrections before this becomes a public issue.

The Hart Crowser analysis uses the following parameters: six rockfalls per year, 137 pedestrians per day, 174 vehicles per day, vehicular length of 15', average vehicular speed 10 mph (or 14.7 fps) pedestrian width 1.5', pedestrian speed 1.5fps. They also use a roadway length of 4100'.

First, the common-sense approach. At 137 pedestrians per day, there are 50,000 per year. If the expected frequency of being hit is 1/18,000, you would expect 2.8 pedestrians to be hit each year. **The analysis assumes six rockfalls per year. Almost 50% would have to strike someone to get 2.8 per year. This alone tells you something is seriously wrong with the analysis**. If I stood on the bank above the road and tried to hit pedestrians with rocks as they went by, I doubt I could hit 50% of them. And half the rockfalls occur at night.

There are only 137 pedestrians per day, occupying a width of 1.5' each. If they all stood in the road for 24 hours, scattered along the road, they would occupy 205', or 1/20th of the total road length of 4100'. So this would indicate a maximum of a 1/20 chance that any pedestrian would be hit by a single rockfall. But a pedestrian is not on the road for 24 hours. The pedestrian is on the road for about 45 minutes, or 1/32nd of the day, indicating that the chance of any pedestrian being hit by any single rockfall event is about 1/640. This is the same number that I will derive independently in the next paragraphs using the AGS method referred to in the Hart Crowser study.

More detailed: Hart Crowser and AGS, Appendix E (2000) use the same equation to determine P(S.H). AGS(2000) calls P(S.H) "Probability of a vehicle occupying the portion of the road onto which a rock falls." It is a function of the width and speed of the vehicle or pedestrian, and the daily numbers of each. (You must use metric equivalents in this equation.) I get the same numbers as Hart Crowser: 1.6×10^{-3} for pedestrians, or 1/625, or 2.2×10^{-3} , or 1/455, for vehicles.

This is the probability that any single rockfall event will hit a vehicle or pedestrian: the probability that a vehicle or pedestrian is occupying that portion of the road when the rock falls on it. It incorporates both space and time.

If the chance that a vehicle will be hit by a single rockfall is 1/455, the chance of being hit by one of the six in a year is 6/455, or about 1/76. For pedestrians, it is 6/625, or about 1/104. From there, it is a simple matter to calculate the per vehicle risk of being hit: 76 X 174 X 365 or about 1/4.8 X 10^6 . For a pedestrian it is 104 X 137 X 365, or 1/5.2 X 10^6 . The risk of death to a pedestrian is therefore about one in every 5.2 million trips using Hart Crowser's assumption that every impact is fatal. If we use the 0.3 probability in Hart and Crowser of death if a vehicle is hit, the risk is about 1 per 16 million vehicle trips.

Intuitively: a 15' long vehicle moving at 15 fps is in danger of being hit by a rockfall for the one second it takes to cross the rockfall path. With 174 vehicles/day, there are 174 seconds/day at which a vehicle is at risk. There are 86,400 seconds in a day. 174 seconds is about 1/496th of a day. The difference between that and the 2.2 X 10^{-3} or 1/455 number derived using AGS 2000 comes from rounding. Using a 5 m long vehicle gives you 1/455, using a 4.5 m long vehicle gives you 1/490. The AGS equation and the method I use in this paragraph are exactly the same except in the form of the equation. Also AGS is done per hour while this paragraph is done per day, but the risk per vehicle or pedestrian works out the same. You can do the same analysis for a pedestrian. It is easy because the pedestrian is also at risk for 1 sec.

AGS (2000), Appendix E uses a second equation to calculate P(S): "the probability of one or more vehicles being hit" from P(S.H.). Using this equation, I get about 1/27,000 as the daily probability of a rock striking a vehicle, and about 1/38,000 as the daily probability of a rock striking a pedestrian. Multiplied by the per-day numbers gives almost exactly the numbers I derived in the previous paragraphs.

I do see one potential problem with the assumptions, particularly for pedestrians. They ignore the width of the rockfall and treat it as a line. But even if the average rockfall is, say 4.5' wide, the pedestrian is at risk for 4 seconds, the time it takes to clear 4.5' plus the width of the pedestrian. This still leaves a risk to the pedestrian of 1 per 1.3 million trips.

None of the above analysis depends upon the condition of the road, rainfall, etc. Like the Hart Crowser analysis, it depends only upon the stated parameters. If any real-life adjustment should be made, it would be to lower the risk of rockfall because many of the larger ones occur during or after heavy rains, when recreational use is lower.

As stated above, I do not understand why Hart Crowser adds a second equation that it calls the "temporal probability." P(S.H) already includes the temporal probability. It is the probability that a vehicle (or pedestrian) is in the impact zone **when the rock falls**. We are assuming the rocks fall at random times at random places. The probability that a car will be hit by a rock is the probability that a car occupies any random 15' wide space, which, in the Waipi'o example, is 174 cars X 1 second/86,400 seconds.

Hart Crowser's second equation is the number of hours that cars (or pedestrians) are on the road in a day, divided by the number of hours in a year. If the road were shorter, the time that cars would be on the road would be shorter, and Hart Crowser's method would say that the risk is less. The length of the road doesn't matter. Imagine if all the rocks fell in one 2000' section of the road and you only analyzed that one section. If the number of rockfalls was the same, and the velocities and vehicle numbers were the same, and driver behavior didn't change, the same number of vehicles would be hit. If that isn't convincing, imagine you added a section of highway where no rocks fell to the analysis. Obviously this would not increase the total risk, even though it would increase the time spent on the road. This is simply the reverse of the prior example.

Are these acceptable risks? That is a judgment call, not an objective question, but applying the average fatality rate in the US to the 50 mile drive from Hilo to the Waipi'o Valley lookout, 1.1 per 100 million vmt, you get one death per 1.8 million trips. The risk of driving to the lookout is greater than the risk of death from rockfalls if you continue down into the valley either as a pedestrian or driver.

I would appreciate it very much if Hart Crowser's engineers would review and respond to this email. --Chris Yuen

---

From: Chang, Carty S <carty.s.chang@hawaii.gov>
Sent: Friday, March 4, 2022 11:02 AM
To: HOTMAIL-Chrisyuenz <chrisyuenz@hotmail.com>; Marsters, Janice <Janice.Marsters@hartcrowser.com>
Cc: Kurata, James K <james.k.kurata@hawaii.gov>
Subject: Introduction between Board Member Yuen and Hart Crowser

CAUTION: External Email

Aloha Board Member Yuen and Janice Marsters,
This is an introductory email to facilitate a meeting to discuss the analysis in the Waipio Valley Road Preliminary Geotechnical Engineering Evaluation commissioned by the County of Hawaii DPW.

Please feel free to schedule a meeting or discussion directly with each other.
Thank you
Carty

From: Marsters, Janice <Janice.Marsters@hartcrowser.com>
Sent: Friday, March 4, 2022 11:37 AM
To: Chang, Carty S <Carty.s.chang@hawaii.gov>; HOTMAIL-Chrisyuenz <chrisyuenz@hotmail.com>
Cc: Kurata, James K <james.k.kurata@hawaii.gov>; Trisler, Dan <Dan.Trisler@hartcrowser.com>
Subject: RE: Introduction between Board Member Yuen and Hart Crowser

Aloha e Carty and Mr. Yuen,

Please give us a few days to review Mr. Yuen's email and early next week we will reach out to set up a meeting.

Regards,
Janice
Janice Marsters
janice.marsters@hartcrowser.com
C: (808) 371.8504

Hart Crowser, a division of Haley & Aldrich
www.haleyaldrich.com

From: Chris Yuen <chrisyuenz@hotmail.com>
Sent: Friday, March 4, 2022 11:49 AM
To: Marsters, Janice <Janice.Marsters@hartcrowser.com>; Chang, Carty S <Carty.s.chang@hawaii.gov>
Cc: Kurata, James K <james.k.kurata@hawaii.gov>; Trisler, Dan <Dan.Trisler@hartcrowser.com>
Subject: Re: Introduction between Board Member Yuen and Hart Crowser

CAUTION: External Email

Aloha, thanks very much for agreeing to a phone meeting. I will make the time whenever it is convenient for you.

I'd like to make it clear that I don't represent the Board--which acts as a group--or the Department in the ongoing discussions with the County on this. The Department has an employee representing it and I don't supervise the employee. I am acting out of concern about the County's shutdown of Waipi'o Valley to the general public as a private citizen and also because it affects the DLNR interest in hiking and hunting access. I think the County's decision was based on a faulty risk analysis.

I am happy talk anytime you are ready but I do feel some time pressure because there is a public hearing via zoom to discuss this at 5:30 pm on March 9. --Chris

From: Marsters, Janice <Janice.Marsters@hartcrowser.com>
Sent: Friday, March 4, 2022 12:08 PM

To: Chris Yuen <chrisyuenz@hotmail.com>; Chang, Carty S
<Carty.s.chang@hawaii.gov>
Cc: Kurata, James K <james.k.kurata@hawaii.gov>; Trisler, Dan
From: Chris Yuen <chrisyuenz@hotmail.com>
Sent: Tuesday, March 8, 2022 3:20 PM
To: Marsters, Janice <Janice.Marsters@hartcrowser.com>; Chang, Carty S
<Carty.s.chang@hawaii.gov>
Cc: Kurata, James K <james.k.kurata@hawaii.gov>; Trisler, Dan
<Dan.Trisler@hartcrowser.com>
Subject: Re: Introduction between Board Member Yuen and Hart Crowser

CAUTION: External Email

Hi, I had expected you to get back to me Monday but I didn't hear from you. I responded to a reporter's inquiries today. I basically gave him what I emailed you. I would still be very interested in your response. --Chris.

<Dan.Trisler@hartcrowser.com>
Subject: RE: Introduction between Board Member Yuen and Hart Crowser

Thank you Chris, we'll get back to you on Monday after we've had time to look at your information.

Regards,
Janice
Janice Marsters
janice.marsters@hartcrowser.com
C: (808) 371.8504

Hart Crowser, a division of Haley & Aldrich
www.haleyaldrich.com

From: Marsters, Janice <Janice.Marsters@hartcrowser.com>
Sent: Tuesday, March 8, 2022 5:19 PM
To: Chris Yuen <chrisyuenz@hotmail.com>
Cc: Kurata, James K <james.k.kurata@hawaii.gov>; Chang, Carty S
<Carty.s.chang@hawaii.gov>; Trisler, Dan <Dan.Trisler@hartcrowser.com>; Pause,

Stephen (Steve) <Steve.Pause@hawaiicounty.gov>
Subject: RE: Introduction between Board Member Yuen and Hart Crowser

Aloha e Mr. Yuen,

I apologize for not getting back to you yesterday. Our rockfall team has been wrapped up with other projects and deliverables.

While we haven't had time to evaluate all your statements in detail, we have looked at the information provided and think there may be a misunderstanding of the nature of our analysis and of the concept of probability versus frequency. We disagree that the risk analysis was faulty, and stand by the conclusions of our report. The AGS methodology is used to grossly quantify observations of slope hazards that are largely qualitative by nature at this phase of the assessment, and to provide a probabilistic framework for stakeholders to make decisions about tolerable and acceptable levels of risk in the interest of public safety. This project was brought about by recognized hazards (both landslide and rockfall events) that have occurred historically on the road and most recently (as of the time of the study) occurring in March 2019. Those hazards remain and may have gotten worse with heavy storm events and since our last survey. While we used a methodology commonly used to estimate risks and compare them to what may be acceptable, we noted in our report the limitations to the model inputs at this initial stage of investigation, and that there are other factors that should be considered in making decisions. We are working with the County to conduct additional investigations beyond this conceptual stage and to develop remediation options, which we anticipate will target critical areas first. That may enable us and the County to make a different assessment of the risk.

Kind regards,
Janice
Janice Marsters
janice.marsters@hartcrowser.com
C: (808) 371.8504

Hart Crowser, a division of Haley & Aldrich
www.haleyaldrich.com

From: Chris Yuen <chrisyuenz@hotmail.com>
Sent: Tuesday, March 8, 2022 9:30 PM
To: Marsters, Janice <Janice.Marsters@hartcrowser.com>
Cc: Kurata, James K <james.k.kurata@hawaii.gov>; Chang, Carty S <Carty.s.chang@hawaii.gov>; Trisler, Dan <Dan.Trisler@hartcrowser.com>; Pause, Stephen (Steve) <Steve.Pause@hawaiicounty.gov>
Subject: Re: Introduction between Board Member Yuen and Hart Crowser

Aloha, and thanks for getting back to me. I understand that you have other priorities, but I do think it is a serious matter that your risk analysis might overstate the risks by 280X and 100X. The County has made a major decision based on this risk analysis. I think that if someone spent a half hour reading what I've written he or she would understand the problem.

Hart Crowser generated two numbers, the estimate of one death per 18,000 pedestrians and the estimate of one death per 170,000 motorists. From these numbers Hart Crowser made some comparisons with common risks. The whole quantitative risk analysis rests on these numbers.

The analysis depends only upon the number of pedestrians and motorists per day, the length of the typical vehicle or the width of the pedestrian, the velocities of each, and the number of rockfalls per year. It doesn't depend on rainfall, the 2019 landslide, etc. Hart Crowser and I put the same numbers into the AGS (2000) equation for P(S.H.) and get the same result. We must differ on what it means. I believe it means the probability that a single rockfall will hit a vehicle or pedestrian. That is what AGS(2000), Appendix E, appears to say. If you examine the equation, it calculates the probability that a vehicle will be in the impact zone when a rock hits. HC says it means the "spatial probability," then multiplies it by the "temporal probability," an adjustment AGS does not make.

If you can justify the 1/18,000 and 1/170,000 numbers, I would appreciate a specific explanation. --Chris.

MĀLAMA I KE KAI ‘O WAIPI‘O, *et al.* vs., MITCHELL D. ROTH, *et al.*
CIVIL NO. 3CCV-22-0000106

Plaintiffs' Exhibit E

From: Chris Yuen
Sent: Sunday, March 13, 2022 10:50 AM
To: Rodenhurst, Ikaika <Ikaika.Rodenhurst@hawaiicounty.gov>; Pause, Stephen (Steve) <Steve.Pause@hawaiicounty.gov>
Subject: Waipi'o Road

Aloha Ikaika and Steve:

I know I am being a pain in the butt on this subject but this was a major decision and I have been trying to explain that it was made on drastically flawed data. The risk analysis depends upon the per-vehicle and per-pedestrian risks. It is worthless without it.

I do not know if you still need to be persuaded. I am hoping that you don't and that the County is searching for a way to modify the emergency decree so that the general public can again have access to the ocean and trails in this treasured area.

If you still need persuading, please consider this: if valid, the Hart Crowser method should work for any reasonable set of numbers. Try putting these numbers in the method they use on p.10-12:

N_V= Number of vehicles/day= 8640 (this equals 1 vehicle every 10 seconds.)
L= Length of vehicle = 5m
V_V= 18 km/hr (5m/sec)
Length of road = 4,000m
V_{DT}= Probability that a rock striking a vehicle will result in death= 1
Ph= rockfalls/yr. =1

You will see that the result is 1.31. According to the Hart Crowser formula, every vehicle using the road (over three million a year, in this example) gets hit by a rock even though there's only one rockfall per year. Also, no method that yields a probability greater than one can be correct. I've worked all this out in the attachment, which also explains in more detail where Hart Crowser went wrong and how to calculate the real probability. You can also reproduce my calculations in less than ten minutes just putting these numbers in the Hart Crowser formula yourselves. Please feel free to share this with Hart Crowser if you want. If I am wrong, I would greatly appreciate someone explaining why. --Chris Yuen

MĀLAMA I KE KAI ʻO WAIPIʻO, *et al.* vs., MITCHELL D. ROTH, *et al.*
CIVIL NO. 3CCV-22-0000106

Plaintiffs' Exhibit F

HARTCROWSER
www.hartcrowser.com

TECHNICAL MEMORANDUM

DATE: October 10, 2019

TO: Robyn Ito, SSFM International

FROM: Janice Marsters

RE: **Geological Hazards Assessment**
Hāmākua Coast Transportation Corridor Study Project
Hāmākua, Hawai'i
3140-016-001

Hart Crowser, Inc. is pleased to submit this memorandum providing a geological hazard assessment of a portion of State Route No. 19, Hawai'i Belt Road (also known as the Hāmākua Highway). Hawai'i Belt Road, Route 19 is located on the northeast coast of Hawai'i Island traversing the Hāmākua and north and south Hilo districts. Route 19 is the section between Hilo and Waimea along the foot of the Mauka Kea shield. The contracted surveyed portion extends from the Wailuku Bridge in Hilo to Mud Lane (five miles east of Waimea), from mile marker (MM) two to mile marker fifty-two, respectively. The location of the project area is shown on Figure 1. Our work was completed in general accordance with our scope and fee estimate provided on June 2, 2017, and our subconsultant agreement with SSFM dated March 29, 2018.

Project Understanding

We understand that HDOT is interested in a study that assists its mission in the preservation, operation and safety of the Highway, a regionally significant transportation corridor. Online research and our knowledge of this area point to the frequent occurrence of rockfall and roadside slope instability along the Hāmākua Highway. Several mitigation projects have been constructed.

We have conducted a geologic hazard assessment for the Hāmākua Coast Transportation Corridor Study Project to be used by the team to develop strategies and methods to avoid and minimize geologic hazards. This memorandum provides a summary of the results of our field reconnaissance and estimated order-of-magnitude costs for addressing hazards.

Scope of Work

Our scope of work included conducting a desktop review of available geologic and soils mapping, topographic information, and LiDAR or other remote sensing data, as well as review readily available press, reports and documents related to past events to understand historic problem areas; conducting a field reconnaissance along the 50-mile corridor to verify general conditions related to geologic hazards, visiting specific problem areas identified in our desktop review, and classifying the corridor into similar areas of hazard; and utilizing the FHWA's Rockfall Hazard Rating System to identify and rank problem

7 Waterfront Plaza
500 Ala Moana Boulevard, Suite 7-240
Honolulu, Hawaii 96813
808.587.7747

areas within the corridor, where the classification system would be portrayed in GIS format to illustrate hazardous conditions within the study area, and develop rough order of magnitude costs for addressing hazards.

Our findings are detailed in the following sections of this memorandum.

Background Data Review

Our assessment included a desktop review of readily available geologic and soils mapping, topographic information, LiDAR/ remote sensing data and Google Earth™ imagery, existing reports and studies, and anecdotal information. LiDAR information from HDOT was evaluated, but was not utilized in our analysis, as the data were provided in raw format and did not contain suitable data up- or down-slope.

We noted that the roadside mile marker sign posts did not exactly align with their marked locations. To resolve this difference for this study, we have distinguished two notations for locations along the highway. Mile markers are the physical locations of the sign posts along the highway and will be abbreviated as "MM" in this study. Mile position is the physical location along the highway centerline relative to the length of the highway and will be abbreviated as "MP". As an example, the 12-mile marker sign is posted at 11.69 miles relative to the absolute length of the highway. So, the true mile position of mile marker 12 is at 11.69 miles from the start of the highway.

Topographic and Geomorphic Features

To assess topographic and geomorphic features, we relied principally on USGS topographic data available as quadrangle maps of the Island of Hawaii. LiDAR data of Route 19 was provided for review, as noted above, but were found to be insufficient for evaluating the corridor. The LIDAR data provided were obtained using a mobile laser scanner mounted to a moving vehicle that drove along the highway. Due to the method used, a digital elevation model (DEM) processed from the data was limited in extent and did not provide enough up- and down-slope coverage to evaluate geologic hazards. Where the ground slopes downhill from the roadway on the makai side of the roadway, no data were collected so a DEM could not be developed.

Our review of the USGS topographic maps found that elevations along Route 19 begin at about sea-level along the coast in Hilo, gradually ascending to about 2,840 feet MSL near Waimea. Along this route the highway crosses several landforms, from broad flat plateaus with gentle slopes to steep slopes adjacent incised gulches. The major landforms that create potential geologic hazards to the highway include the steep oceanfront cliffs, incised gulches/stream valleys, and roadcuts through moderate slopes:

Steep oceanfront cliffs. From MM 2 approaching MM 7 and from MM 13 to MM 21, the highway traverses along the oceanfront atop the bluff, which is defined by basalt cliffs and steep slopes up to 100 feet high. Stream valleys incise the cliffs as they meet the ocean. Along the highway, these stream valleys are spanned by bridges. In several locations along the highway roadcuts are on the order of 50 feet high but most are less than 25 feet.

Incised gulches with stream valleys. From MM21 to MM 29, the highway crosses several gulches/stream valleys with steep incised slopes of up to 100 percent gradient and up to 1,100 feet high. The road through this section is supported on a bench cut into the steep cliff creating high steep cuts immediately mauka of the highway and steep drop-offs on the makai side. The stream valleys are spanned by bridges.

Roadcuts in moderate slopes. From MM 7 approaching MM 13 and from MM 29 to MM 52, the highway traverses moderate slopes with many roadcuts. Most of the roadcuts are less than 25 feet high but some approach 50 feet. As above, bridges span the stream crossings which are more commonly stream channels in upper elevations.

Geologic and Soil Mapping

The corridor geology is mapped in *Geologic Map of the State of Hawai'i, Sheet 8—Island of Hawai'i* (Sherrod et al. 2007). A majority of the corridor has been mapped as Pleistocene Hāmākua Volcanics' Lava Flows (Qhm) of alkalic and transitional basalt in the form of 'a'ā and pāhoehoe, as well as scoria cone vent deposits (Qhmc). Secondary surficial deposits mapped include Holocene and Pleistocene Laupāhoehoe Volcanics' lava flows of 'a'ā and blocky 'a'ā with pāhoehoe found locally (Qly), as well as 'a'ā and pāhoehoe (Ql) with Benmoreite lava flows (Qlb). Minor mapped units include Holocene and Pleistocene Laupāhoehoe Volcanic scoria cones (Qlc) with two Benmoreite cones (Qlbc) and tephra-fall deposits of lapilli and ash (Qla).

The surficial soils along the corridor are mapped in the Natural Resources Conservation Service (NRCS) Web-based soil survey (NRCS 2006). A half-mile buffer from the centerline of Route 19 was used to create an area of interest to identify seven soil types mapped within the project corridor. The soil types are described below, starting in Hilo from the Wailuku River to Mud Lane:

Between the Wailuku River and Maulua Gulch, the soils are mapped as Hilo hydrous silty clay loam derived from basic volcanic ash over basalt. These soils are described to have 0 to 35 percent slopes, occur at 0 to 1,100 foot elevations, and receive 130 to 200 inches of mean annual precipitation. Gulches and stream-valley features in this area are mapped as the Hilo rock outcrop complex, similarly derived from basic volcanic ash over basalt. This complex is described to have 35 to 100 percent slopes, occur at 0 to 1,100 foot elevations, and receive 130 to 200 inches of mean annual precipitation.

Between the Maulua Gulch and Honoka'a town, the soils are mapped as 'Ō'ōkala medial silty clay loam derived from basic volcanic ash. These soils are described to have 0 to 35 percent slopes, occur at 0 to 1,100 foot elevations, and receive 75 to 138 inches of mean annual precipitation. Gulches and stream-valley features in this area are mapped as the 'Ō'ōkala rock outcrop complex, similarly derived from basic volcanic ash over basalt. This complex is described to have 35 to 100 percent slopes, occur at 0 to 1,100-foot elevations, and receive 75 to 138 inches of mean annual precipitation.

For the same area and extending further west within the project corridor, the soils are mapped as Honoka'a highly organic hydrous silty clay loam derived from basic volcanic ash. These soils are described to have 0 to 35 percent slopes, occur at 2,100- to 4,000-foot elevations, and receive 79 to 150 inches of mean annual precipitation. Gulches and stream valley features in this area are mapped as the Honoka'a rock outcrop complex, similarly derived from basic volcanic ash over basalt. This complex is described to have 35 to 100 percent slopes, occur at 1,100 to 4,000 foot elevations, and receive 79 to 150 inches of mean annual precipitation.

In the area of interest between Kalopa Gulch (MP39.2) and Honokaia Gulch (MP46.8), two additional soil types are mapped: Honoka'a hydrous silty clay loam and Kuka'iau medial silty clay loam. The Honoka'a hydrous silty clay loam is derived from volcanic ash and is described to have 0 to 35 percent slopes, occur at 1,100- to 2,200-foot elevations, and receive 79 to 150 inches of mean annual precipitation. The Kuka'iau medial silty clay loam is derived from volcanic ash and is described to have 0 to 35 percent slopes, occur at 1,100- to 1,500-foot elevations, and receive 70 to 100 inches of mean annual precipitation.

Geologic Hazards

Landslide and rockfall hazards for the State of Hawai'i are discussed in Chapter 8 of the 2013 Update of the Multi-Hazard Mitigation Plan (HDOD 2013). Three main categories of land failure are listed: landslides, debris flows, and rockfalls, which can be distinguished by the initiating phenomena. The initiation point of the three failures are reported to be typically along bedding planes or materials that often form weak strata, such as loose or weakly bonded sands, clays, or volcanic ash. Strata of jointed or blocky rock, especially when over a layer of weak strata, are also common points of origin for land failures (Jellinger 1977). Weak strata can also be undermined or lose strength when exposed to natural forces such as rainfall or earthquake shaking. Two natural forces that have been identified by the state as significant factors in land failures are high intensity rainfall and seismicity. Hawai'i Island is both a volcanically and seismically active region where landslide events are often triggered by earthquakes. Although bedding planes and weak strata are the reported typical causes of land failure, these features are not widespread in the project area.

A doctoral dissertation developed earthquake-induced landslide hazard maps for the Island of Hawai'i (Namekar 2013). Using empirical and analytical models in conjunction with data of historical earthquake-induced landslide locations, the study developed hazard maps based on varying levels and sources of shaking. The hazard maps show high hazard ratings in several areas of North Kohala, Hāmākua, and North Hilo under some of the higher shaking levels and with close proximity to the corridor. These high hazard ratings reflect the steep slopes, weak soils, weathered rock, and high rainfall conditions that persist within some areas of the corridor. The study also noted the correlation of rock slope failures that were influenced by the presence of pyroclastic materials. These pyroclastic materials can act as the weak strata described above. The generated earthquake induced hazard maps identify high landslide hazard susceptibility along all the incised gulches and stream valleys/channels of the Hāmākua corridor, yet highway roadcuts were not distinguishable with the resolution of the generated hazard maps.

Seismic events have been identified as a significant trigger for slope failures and, in a 2007 report, a reconnaissance along Highway 19 was performed to observe damage resulting from the October 15, 2006 earthquakes on Hawaiʻi Island (Medley 2007). The earthquake epicenters at Kīholo Bay and Mahukona (Hāwī) had moment magnitudes of 6.7 and 6.0, respectively. Following the earthquakes, a field reconnaissance was completed to identify areas of slope failure. Table 1 below summarizes the locations of slope failures and observations at sites within the project corridor. Six slope failures were identified, including 3 shallow soil slides from road cuts, one embankment failure, one rockfall, and one slope failure that appears to be a deeper slump or earthflow type feature. Few specific details of the slope failures are provided, but the cutbank failures were noted to include the upper 3 to 5 feet of soil, and the rockfall was noted to expose tree roots in the cracks of the rocks where the rockfall occurred. It was also noted that it was not clear which landslides were directly related to the earthquake and not the result of the regular rainfall in the project area (Medley 2007). These sites are shown on Figure 2.

Table 1 – Landslides from the October 15, 2006 earthquake

Station	Location	Lat. (N degs)	Long (W degs)	Feature	Comments
3	S. of Kepehu Camp	19.9571	-155.1971	Road cut slides	Slides within pre-existing slide bounds; 3-5 foot thick slides; soil failed over weathered rock.
4	Near Ōʻōkala, old road beneath Hwy 11 bridge	20.009	-155.2867	Road cut slides	Soil slope failed across road? Top 1/3 of slope.
5	Near Kūkaʻiau, Hwy 11, MP 32	20.0273	-155.3394	Road cut slides	Several small slides not contained by pre-existing netting.
6	Near Paʻauilo, MP 35, Hwy 11	20.0328	-155.3545	Embankment at bridge abutments	Fill at south approach to bridge failed; half of roadway fell into stream
9	Honokaʻa-Waimea, Hwy 19	20.0711	-155.4942	Rock fall	Active rockfall clearance; tree roots in rock fractures.
10	East side Waimea, Hwy 19	20.0456	-155.5866	Landslides (?)	Unknown if these fresh scarps are result of EQ: many observed.

Aerial Imagery Review

We reviewed aerial imagery from Google Earth™ to identify geologic hazards on the makai side of the highway where the ground sloped downward and was not visible during our road surface reconnaissance, as noted previously.

Our methodology consisted of reviewing overhead imagery from the default photo year on Google Earth™ along the route. During our review, we looked for obvious slope failures, bare areas adjacent the roadway, and abrupt changes in topography, which could be indicative of slope movement. We looked where the highway was near steep slopes, including within 100 feet or less of the ocean cliff, at stream crossings (culverts) and bridge abutments. When we identified areas of potential hazard, we observed conditions in overhead imagery from several years and also entered "street view" to evaluate visible signs of hazardous conditions or distress. Due to limitations in the time and budget for the field effort, we did not visit these locations in the field.

A summary of our observations is included in Appendix A and our evaluations of these locations are described in the Evaluation section of this report. The locations of these areas are shown on Figure 2.

Historical and Anecdotal Information

We located articles in newspapers and magazines that addressed geologic hazards within the project route. The articles we located are briefly summarized below; locations of the described sites are shown on Figure 2:

1. A 2007 article in the Honolulu Star Bulletin noted costs to the state after the October 15, 2006 earthquake. These costs included resurfacing damaged roads, clearing rockfall and landslide debris from highways, providing a temporary bypass road at Ka'awali'i Bridge, and repairing the Honoka'a Bridge (Park 2007). This article documents rockfall, landsliding, and bridge failure within the project route, but does not elaborate on the quality of the work that was done. The Honoka'a Bridge was not identified along Highway 19 so was not explored in the field.

2. A 2011 article in Big Island Video News described netting installation at Laupāhoehoe Gulch and similar work at nine more sites in the Maulua, Laupāhoehoe, and Ka'awali'i gulches (Corrigan 2007). The work was described to include cutting trees, clearing and grubbing, rock scaling, and [installing] wire mesh over the cleared slopes. This article documents rockfall hazards within the project route.

3. In an article in National Driller magazine (2012), installation of tieback anchors in Honomū and Laupāhoehoe Gulches is described. Honomū Gulch is described as a failing earthen slope that required 29 anchors up to 60 feet deep. The Laupāhoehoe site is described as a failing rock wall/walls that required 64 anchors up to 65 feet deep to stabilize. The article does not provide further detail on the earth movement but, based on anchor lengths, the article documents deep

landsliding at least in Honomū Gulch, and possibly Laupāhoehoe, not the more common shallow landsliding or rockfall prevalent elsewhere within the corridor.

4. A 2015 article noted a plan to install anchored wire mesh in Laupāhoehoe Gulch. The article described a relatively high frequency of rockfalls. Rockfalls were reported as often as daily, and with typical boulder diameters of about two feet, although reportedly sometimes as big as small cars (Stewart 2015). This article documents rockfall hazards within the project route.

HDOT provided us with field notes titled "Gulches Rockfall & Debris Survey" and dating from February 20, 2018 to March 4, 2018 for the three main gulches within the project area: Maulua, Laupāhoehoe, and Ka'awali'i. The notes were also summarized in a single document. The summary data provided date, time, location, and notes for each entry. The notes describe rock and vegetation obstructions to the highway. The rocks were described to be about a foot or less in most cases, with less frequent occurrences of rocks up to a couple feet. From the summary data we noted two main concerns: rockfall and landsliding. We categorized rockfall as instances where only rocks were noted and landslides as instances where soil with or without rocks was noted. The occurrences of each type are summarized in Table 2. The locations could not be mapped as they were not provided with the documents.

Table 2 – HDOT Gulches Rockfall & Debris Survey Summary

Location	**Rockfall**	**Landslide**	**Notes**
Maulua Gulch	35	1	Most rocks less than 0.5-foot and up to 1-foot in diameter. The landslide had rocks about 1-foot in diameter.
Laupāhoehoe Gulch	11	0	Most rocks less than 0.5-foot and up to 1-foot in diameter. No sliding noted.
Ka'awali'i Gulch	39	2	Most rocks less than 0.5-foot and up to 3-foot in diameter. The landslide had volumes of approximately one bucket load and one cubic yard. The size of the bucket was not detailed.

HDOT also provided us with an excerpt from the "Rockfall Protection Study at Various Locations, Statewide, Hawaii" which was prepared by AECOM in April of 2015. The provided pages contain tables of the top ten rockfall risk sites for each of the state districts including the District of Hawai'i, in which all sites listed are along Highway 19. The tables list the highway name and number, the beginning and end mile positions, the side of the highway, annual daily traffic count, slope height in feet, the total RHRS score, and an estimated cost. It is unclear if the estimated cost represents possible costs of damages or mitigation costs. The excerpt is included as Appendix B. The top 10 sites identified in the study are shown on Figure 2.

Field Reconnaissance

We completed field reconnaissance of the project route from August 13 through 17, 2018. The purpose of the reconnaissance was to survey sites of geologic concern identified in our desktop review. Due to time constraints and the lack of a LiDAR based DEM on the makai side of the highway, we focused our field reconnaissance on the mauka side of the highway.

Limitations of the field work included limited access where traffic hazards were present and limited visibility from vegetative obstructions.

The following sections describe the methods we used and the findings of our field work.

Rockfall Hazard Rating System (RHRS) Surveys

Where slopes were adjacent upslope of the highway, we utilized the Federal Highway Administration's (FHWA) Rockfall Hazard Rating System (RHRS), an accepted hazard classification system to identify and rank hazardous road-adjacent slopes. The RHRS calculates a relative hazard "score" for sites based on the sum of the numerical rankings of nine factors. The nine factors include: slope height, ditch effectiveness, average vehicle risk (AVR), percent of decision sight distance, roadway width, geologic characteristics, block size/volume of rockfall, climate and presence of water, and rockfall history. For each site evaluated, each factor is considered and scored in accordance with the RHRS methodology. The individual scores are then summed to reach a total relative hazard score. Summary data and score tables are included as Appendices C-1 and C-2.

The RHRS methodology is described in detail in Appendix C-4. Our scoring methodology followed the criteria noted in Appendix C-3, and as outlined in Appendix C-4. Additionally, AVR was based on average daily traffic (ADT) from the 2014 Annual Average Daily Traffic data from the DOT Highways Division Road Inventory of Hawai'i Route 19 (HDOT). An updated traffic count was not completed for our analysis.

Our desktop evaluation identified 17 potential geologic hazard sites. Four of these sites had more than one slope of concern where a final total of 23 sites were visited in the field. One of the sites, a geologic hazard assessment at a bridge, was not assessed using the RHRS and a second site was a low slope, so was not further assessed, resulting in RHRS scores for 21 total locations. The locations of the field sites are shown on Figure 3.1, and data and scores are shown in Appendices C-1 and C-2.

Findings

We found the corridor to be subject to geologic hazards associated with the makai side of the highway (mostly proximity to steep slopes), the mauka side of the highway (mostly rockfall and shallow landsliding), and others. Our findings related to these is discussed below.

Downslope and Roadway Hazards

Our evaluation of hazards on the makai side of the roadway relied only on our desktop review. Our field reconnaissance did not address downslope hazards due to the lack of visibility of such features from the road and project budget constraints. Our review of anecdotal information found few downslope hazards; however, our geomorphic review coupled with our review of aerial imagery found four conditions which create potential geologic hazards to the roadway. These four conditions and the quantity of each type are summarized in Table 3. These sites are shown on Figure 3.2.

Table 3 – Downslope and Roadway Hazards (DRH)

Condition	Description	# of Sites	Notes
Fill Stability/Distress	Aerial images identified areas where the slopes of embankment fills appeared to have failed, been repaired, or exhibited distress. Where embankment fills are steep, poorly compacted or become saturated, ground failure may occur.	3	Occurs mostly in the oceanfront cliffs landform and associated with culvert fills.
Downhill Cliff Encroachment	Where the roadway is constructed near the steep oceanfront cliffs, erosion causes retreat of the top of the bluff, eventually reaching the roadway	8	Occurs mostly in oceanfront cliffs landform. Delineated as where roadway is located within approximately 100 feet or less of the ocean cliff.
Possible Culverts	Undersized, poorly maintained or plugged culverts may be present which can result in erosion, flooding or even embankment failure.	14	Possible culvert locations were identified as where streams intersect the roadway, but bridges are not present. Culverts were not field-evaluated. Occurs throughout the corridor.
Bridge Abutments	Bridge abutments built into steep slopes may not have adequate setbacks or become undermined.	30	Bridges are located throughout the corridor. Only the Ka'awali'i Bridge was field-evaluated for geologic hazards and was found to have a scoured abutment at one end. Other bridges may have similar conditions.

Upslope Hazards

Our evaluation of hazards on the mauka side of the highway found rockfall and shallow landslides to be the predominant hazards to the corridor. Rockfall as a significant hazard is indicated by numerous anecdotal reports, previous studies, the general geology and frequent rockfall events. Shallow landsliding as a hazard is indicated by similar sources. Most sources suggest shallow landsliding is much less frequent than rockfall, but the 2006 earthquake report documented four shallow soil slides but only one rockfall. The reason for this discrepancy is not known and may be the result of classification rather than physical occurrences. Our research also found mention of two potential deep-seated landslides. The upslope rockfall hazards we identified are summarized in Table 4 and shown on Figure 3.1. Figures 4.1 through 4.11 show the upslope areas with RHRS score ranges. Other upslope hazards are summarized in Table 5, but their specific locations were not indicated in the information available to us so they could not be mapped on report figures.

Table 4 – Upslope Rockfall Hazards

Site	Location (MP's)	Position	RHRS Score	Notes/Other	Rockfall Mitigation
T1A	MP 20.97 to 21.37	Mauka	333	• AECOM Top 10, Rank 1, Score 411 • South Maulua Gulch	No
T1B	MP 20.97 to 21.07	Makai	186	• South Maulua Gulch	No
T2	MP 22.07 to 21.17	Mauka	351	• AECOM Top 10, Rank 3, Score 389 • North Maulua Gulch	No
T3A	MP 25.67 to 25.97	Mauka	309	• AECOM Top 10, Rank 2, Score 395 • South Laupāhoehoe Gulch	Yes, Netting
T3B	MP 25.97 to 26.07	Mauka	207	• AECOM Top 10, Rank 5, Score 261 • South Laupāhoehoe Gulch	No
T4	MP 26.32 to 26.67	Mauka	291	• AECOM Top 10, Rank 4, Score 350 • North Laupāhoehoe Gulch	Yes, Netting
T5	MP 26.67 to 26.79	Makai	195	• North Laupāhoehoe Gulch	Yes, Netting
T6A	MP 27.66 to 28.06	Mauka	297	• AECOM Top 10, Rank 9, Score 240 • South Ka'awali'i Gulch	No
T6B	MP 28.36 to 28.66	Mauka	246	• North Ka'awali'i Gulch	No
T7A	MP 12.44 to 12.64	Mauka	177	• AECOM Top 10, Rank 7, Score 240 • South Honomū Gulch	Yes, Retaining Wall

Table 4 – Upslope Rockfall Hazards

Site	Location (MP's)	Position	RHRS Score	Notes/Other	Rockfall Mitigation
T7B	MP 12.44 to 12.64	Makai	171	• AECOM Top 10, Rank 8, Score 240 • South Honomū Gulch	No
T7C	MP 12.77 to 12.92	Mauka	189	• AECOM Top 10, Rank 10, Score 238 • North Honomū Gulch	No
T7D	MP 12.77 to 12.92	Makai	189	• North Honomū Gulch	No
T11A	MP 15.8 to 16.0	Mauka	123	• South Umauma Gulch	Yes, Netting
T11B	MP 16.05 to 16.2	Mauka	81	• North Umauma Gulch	Yes, Netting
T9	MP 29.72 to 29.92	Mauka	117	• South Ka'ula Gulch	No, Retaining Wall
T15	MP 30.69 to 30.79	Mauka	87	• Kaholo Gulch	No, Retaining Wall
T12A	MP 33.24 to 33.36	Mauka	87	• Lauhala Gulch	No
T10	MP 33.64 to 34.04	Mauka	153	• Kūka'iau Gulch	No
T13	MP 41.69 to 41.76	Mauka	81	• Kahaupu Gulch	No, 2 Retaining Walls
T14A	MP 43.99 to 44.39	Mauka	93	• Kainapahoa Gulch	No

Table 5 – Other Upslope Hazards

Type	Notes/Comments
Shallow Landslides	Four shallow landslides were identified in the 2006 Kīholo Bay Earthquake report by Medley. HDOT field notes also mention a few shallow landslides. During our field reconnaissance, we observed two primary surface conditions where vegetation did not obscure the ground: rock outcrop and mixed rock/residual soils. Some areas had both surface conditions. We noted that, on the edges of rock outcrops in some places, the rock transitioned to rock/residual soils. We noted that apparent shallow landslide scars were present at some of these transition locations. These transition zones appear

Table 5 – Other Upslope Hazards

Type	Notes/Comments
	to be at least one source of shallow landsliding in the project study area. Others could not be determined, but any steep slope with mixed rock/residual soils is a possible future shallow landslide.
Deep Landslide	The mention of anchors up to 65-feet long in the literature to stabilize slopes at both Honomū and Laupāhoehoe suggests deep landslides occurred. Deep landslides usually occur where residual soils are deep. Roadcuts exacerbate landslide magnitude and frequency. We were not able to identify specific areas within the corridor where deep landsliding is likely but note deep landslides as a hazard within the corridor. Although an apparent infrequent hazard, stabilizing deep landslides can be disproportionately expensive.
Failed retaining Wall	Retaining walls were reported to have been stabilized by deep anchors in the study area. It was not clear if the walls were part of a deep landslide buttress or were existing walls failing from high earth- or hydrostatic pressures. We were not able to identify the location of the stabilized retaining wall noted in our literature search. However, we identified walls within the corridor that may be prone to failure (see Other Hazards section of report, below), and note wall failure as a general hazard to the corridor.

Other Hazards

During our evaluation, we noted additional hazards besides those specifically related to the mauka or makai side of the highway. These are briefly summarized below.

Geologic hazards at Ka'awali'i Bridge structure were assessed as the bridge was identified in the October 6, 2015 Earthquake Reconnaissance report. No significant geologic hazards were observed affecting the bridge, except we noted evidence of scour at the base of the north-mauka abutment. The scour extended below the rock/grout material about 3.5 feet at about 2 feet above the base of the abutment.

Five retaining walls were identified in our field reconnaissance. One of the walls appears to be stabilizing the roadcut slope and seems to correspond with retaining wall supporting a failed earthen slope described in the 2012 National Driller article. Three of the five walls appeared to support telephone poles directly upslope of the retaining walls. The fifth wall was built at the footing of the structural supports the slope below a column of the Ō'ōkala Plant overpass. The 2012 article also discusses the stabilization of two retaining walls (locations not identified); however, due to these instances, the retaining walls described above are considered potential hazards. The locations of these retaining walls are shown on Figure 2 with labels corresponding to their site ID.

Conclusions

Based on our evaluation, multiple geologic hazards are present within the Hāmākua Corridor study area. We classified the corridor into differing geologic hazard areas and summarized potential mitigation costs for these areas, as feasible. The following sections discuss the hazard classifications and mitigation costs.

Corridor Classifications

From our evaluation, we identified the following classes of hazards:

- Unmitigated rockfall and landslide hazards. Most commonly in the incised gulches and stream valleys. Characterized chiefly by steep and/or convex slopes composed of rock, residual soils, or a combination of the two.
- Downhill cliff encroachments. Proximity of roadway to steep downhill slopes most commonly occurring at the oceanfront cliffs, which are typically 100 feet high.
- Culverts/embankment fills. Located at stream/roadway intersections. Indications of past failures/repairs resulted in classification of culverts and other fills as locations of potential future failure.
- Other geologic hazards. Scour affected at least one bridge abutment. Other abutments were not evaluated but may be at risk.

Figures 3.1, 3.2, 4.1 through 4.11, and 5.1 through 5.8 show the locations of these hazards.

Because of the variations between the hazards identified, the unknowns associated with each, and the preliminary nature of our evaluation, it is not possible to compare and rank specific hazards and hazardous areas within the corridor. However, based on the spatial occurrence of hazards (where locations could be identified), we have generated a hazard density map of geologic sites along Highway 19. Areas with higher density are expected to be affected by geologic hazards more frequently, while those with lower density affected less frequently. This corridor classification gradient is shown on Figure 6.

Mitigation Cost Estimates

To estimate mitigation costs where sufficient information was available, we considered typical mitigation methods for each hazard and what the most likely method would be at each site. We concluded that the following methods of mitigation would most likely be required to address the identified hazard areas.

1. Rockfall Hazards. Rockfall netting is most appropriate to address rockfall hazard.

   a. Drapery netting is the most economical measure where an adequate ditch is located at the base of the slope, so drapery netting was selected for such locations. Unit prices of $6 to $12/sq ft were used in our cost estimates for these areas. If there is no ditch, a ditch may be constructed where there is adequate shoulder space. Shoulder widths are listed in Table 6.

   b. Where there is not adequate room for a ditch, anchored netting would be required. Anchored netting was assumed for such locations. Unit prices of $14 to $20/sq ft were used in our cost estimates for these areas.

   c. Individual rock bolting, lashing or other measures may be necessary in lieu of or to supplement netting, but determining the need for such measures would require site specific studies, so cost estimates could not be developed for these measures at this conceptual stage.

2. Shallow and Deep Landsliding. Mitigation measures can vary greatly for stabilization of shallow and especially deep landsliding. Where adequate right-of-way is available, grading to more stable slopes may be effective for shallow or deep landsliding. Elsewhere, an anchored mesh, similar to anchored rockfall netting has been successfully constructed to stabilize shallow slopes. As noted in Honomū and Laupāhoehoe gulches, deep anchors were required to stabilize a deep landslide and failing wall, and buttress and retaining walls may be necessary for such deep landslides elsewhere. To determine appropriate mitigation measures, site specific studies would be required, so cost estimates could not be developed for these areas at this conceptual stage.

3. Downhill Cliff Encroachment. Similar to landsliding, mitigation measures can vary greatly for addressing encroachment of the seacliff on the roadway. If the cliff is sufficiently stable and erosion resistant, a retaining wall or mechanically stabilized earth (MSE) fill section might provide for an adequate makai roadway shoulder. In other locations, moving the roadway mauka to avoid further repairs may be necessary. To determine appropriate mitigation measures, site specific studies would be required, so cost estimates could not be developed for these areas at this conceptual stage.

4. Embankment Repair. Embankment repair would typically require grading, MSE fills or retaining walls to address if found to be unstable. The level of evaluation we conducted did not determine the stability of existing embankments, but we observed embankments similar to others that have required repair. To determine appropriate mitigation measures, site specific studies would be required, so cost estimates could not be developed for these areas at this conceptual stage.

5. Culvert Replacement. We did not evaluate culverts in detail but identified 14 locations with culverts as shown in Figure 3. Further assessment is needed but, based on information from SSFM, a typical culvert replacement would be on the order of $400,000.

6. Bridge Abutments in Steep Slopes. We did not look at bridge abutments founded within steep slopes, except at the Ka'awali'i Bridge (identified in the October 6, 2015 Earthquake Reconnaissance report). We observed scour at one of the bridge abutments. Scour or other unstable conditions may exist at other bridges and should be evaluated. To determine appropriate mitigation measures, site specific studies would be required, so cost estimates could not be developed for these areas.

Table 6 below summarizes our estimated costs for rockfall mitigation. Mitigation costs for other hazards could not be characterized sufficiently to allow for a reasonable estimation of costs at this conceptual stage.

Table 6. Rockfall Mitigation Measures and Estimated Costs

Site	Mitigation	Units	Unit Costs	Total Costs	Notes/Comments
T1A	Anchor Netting	1,080,000 ft^2	$14 to $20/sq ft	$15,120,00 - $21,600,00	No ditch present. Shoulder widths approximately 4 to 6 feet.
T1B	Anchor Netting	50,000 ft^2	$14 to $20/sq ft	$700,000 $1,000,000	No ditch present. Shoulder widths approximately 5 to 7 feet.
T2	Anchor Netting	470,000 ft^2	$14 to $20/sq ft	$6,580,000 - $9,400,000	No ditch present. Shoulder widths approximately 5 to 6 feet.
T3A	Anchor Netting	500,000 ft^2	$14 to $20/sq ft	$7,000,000 - $10,000,000	No ditch present. Shoulder widths approximately 2 to 18 feet.
T3B	Anchor Netting	40,000 ft^2	$14 to $20/sq ft	$560,000 $800,000	No ditch present. Shoulder widths approximately 13 to 18 feet.
T4	Anchor Netting	690, 000 ft^2	$14 to $20/sq ft	$9,660,000 - $13,800,000	No ditch present. Shoulder widths approximately 3 to 13 feet.
T5	Anchor Netting	60,000 ft^2	$14 to $20/sq ft	$840,000 $1,200,000	No ditch present. Shoulder widths approximately 7 feet.
T6A	Anchor Netting	610,000 ft^2	$14 to $20/sq ft	$8,540,000 - $12,200,000	No ditch present. Shoulder widths approximately 5 to 9 feet.
T6B	Anchor Netting	390,000 ft^2	$14 to $20/sq ft	$5,460,000 - $7,800,000	No ditch present. Shoulder widths approximately 7 to 12 feet.
T7A	Anchor Netting	80,000 ft^2	$14 to $20/sq ft	$1,120,000 - $1,600,000	No ditch present. Shoulder widths approximately 5 to 6 feet.
T7B	Anchor Netting	170,000 ft^2	$14 to $20/sq ft	$2,380,000 - $3,400,000	No ditch present. Shoulder widths approximately 5 to 6 feet.
T7C	Anchor Netting	130,000 ft^2	$14 to $20/sq ft	$1,820,000 - $2,600,000	No ditch present. Shoulder widths approximately 6 to 7 feet.

Table 6. Rockfall Mitigation Measures and Estimated Costs

Site	Mitigation	Units	Unit Costs	Total Costs	Notes/Comments
T7D	Anchor Netting	70,000 ft^2	\$14 to \$20/sq ft	\$980,000 - \$1,400,000	No ditch present. Shoulder widths approximately 6 to 7 feet.
T11A	Anchor Netting	90,000 ft^2	\$14 to \$20/sq ft	\$1,260,000 - \$1,800,000	No ditch present. Shoulder widths approximately 8 to 10 feet.
T11B	Drapery Netting	40,000 ft^2	\$6 to \$12/sq ft	\$240,000 \$480,000	Ditch with width of 15 feet tapering down to 2' for 60 feet and then continues for approximately 125 feet with a 2-foot width. Shoulders are approximately 10 feet wide.
T9	Anchor Netting	90,000 ft^2	\$14 to \$20/sq ft	\$1,260,000 - \$1,800,000	No ditch present. Shoulder widths approximately 8 to 9 feet.
T15	Anchor Netting	30,000 ft^2	\$14 to \$20/sq ft	\$420,000 - \$600,000	No ditch present. Shoulder widths approximately 5 to 10 feet.
T12A	Anchor Netting	70,000 ft^2	\$14 to \$20/sq ft	\$980,000 - \$1,400,000	No ditch present. Shoulder widths approximately 9 to 15 feet.
T10A	Anchor Netting	240,000 ft^2	\$14 to \$20/sq ft	\$3,360,000 - \$4,800,000	No ditch present. Shoulder widths approximately 6 to 13 feet.
T13	Anchor Netting	50,000 ft^2	\$14 to \$20/sq ft	\$700,000 - \$1,000,000	No ditch present. Shoulder widths approximately 8 to 9 feet.
T14A	Anchor Netting	450,000 ft^2	\$14 to \$20/sq ft	\$6,300,000 - \$9,000,000	No ditch present. Shoulder widths approximately 8 to 11 feet.

- The above mitigation cost estimates are approximate and should not be considered "Engineer Estimates", but rough order of magnitude costs suitable for conceptual planning purposes only.
- Site specific studies are required to confirm the need for mitigation, determine the type of mitigation appropriate for each site, and for design of mitigation measures.

Summary

Hart Crowser, Inc. has conducted a geologic hazard assessment as part of the Hāmākua Coast Transportation Corridor Study Project, a study to assist Hawai'i DOT's mission in the preservation, operation and safety of the Hāmākua Highway, a regionally significant transportation corridor. Based on our evaluation, multiple geologic hazards are present within the Hāmākua Corridor study area. We classified the corridor into differing geologic hazard areas and summarized potential mitigation costs for these areas, as feasible.

Please contact us if you have any questions regarding this memorandum.

Shyun Ueno Field Geologist	Janice Marsters Project Manager	Tim Blackwood Sr. Consultant

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Appendix C-1

Rockfall Hazard Rating System Data Summary

Site	Field Name	Slope Height	Ditch Effectiveness	Average Vehicle Risk	Percent of Decision Sight Distance	Roadway Width Including Paved Shoulders	Geologic Character				Block Size or Volume of Rockfall/Event		Climate and Presence of Water on Slope	Rockfall History
							Case 1		Case 2					
							Structural Condition	Rock Friction	Structural Condition	Difference in Erosion Rates	Block Size (ft)	Volume (cubic yards)		
1	T1A	350	limited	57	19	34	D / R	R / I	Occasional	Moderate	4		27	Many
2	T1B	52	limited	14	15	34	D / R	R / I	Occasional	Moderate	1		27	Many
3	T2	259	limited	129	20	37	D / R	R / I	Occasional	Moderate	2		27	Many
4	T3A	230	limited	53	52	53	D / R	R / I	Occasional	Moderate	4		27	Many
5	T3B	27	limited	18	10	44	D / R	R / I	Occasional	Moderate	1		27	Many
6	T4	250	limited	61	14	48	D / R	R / I	Occasional	Moderate	2		27	Many
7	T5	49	limited	21	11	46	D / R	R / I	Occasional	Moderate	2		27	Many
8	T6A	270	limited	57	13	38	D / R	R / I	Occasional	Moderate	2	1	27	Many
9	T6B	160	limited	43	14	44	D / R	R / I	Occasional	Moderate	2		27	Many
10	T7A	29	limited	29	20	36	D / R	R / I	Occasional	Moderate	2	2	27	Few
11	T7B	35	limited	29	20	36	D / R	R / I	Occasional	Moderate		1	27	Few
12	T7C	70	limited	22	29	34	D / R	R / I	Occasional	Moderate	1	1	27	Few
13	T7D	70	limited	22	29	34	D / R	R / I	Occasional	Moderate	1	1	27	Few
14	T11A	30	limited	29	50	34	D / R	R / I	Occasional	Moderate	2		27	Few
15	T11B	35	good	22	50	40	D / R	R / I	Occasional	Moderate	1		27	Few
16	T9	32	limited	29	60	32	D / R	R / I	Occasional	Moderate	1		27	Few
17	T15	17	limited	14	70	38	D / R	Infilled	Occasional	Moderate	1		27	Few
18	T12A	30	moderate	17	100	47	-	R / I	Occasional	Moderate	1	11	27	Few
19	T10	44	limited	57	60	44	D / R	R / I	Occasional	Moderate	1	11	27	Few
20	T13	25	limited	1	133	56	D / R	R / I	Occasional	Moderate	1		27	Few
21	T14A	43	limited	48	133	43	D / R	R / I	Occasional	Moderate	1		27	Few

D/ R = Discontinuous Joints, Random Orientation

R / I = Rough, Irregular

Appendix C-2

RHRS Scoring Summary with Ranking

Site	Field Name	Slope Height	Ditch Effectiveness	Average Vehicle Risk	Percent of Decision Sight Distance	Roadway Width Including Paved Shoulders	Geologic Characteristics	Block Size or Volume of Rockfall/Event	Climate and Presences of Water on Slope	Rockfall History	RHRS Score	Rank
1	T1A	27	27	27	81	27	9	81	27	27	333	2
2	T1B	9	27	3	81	27	9	3	27	0	186	11
3	T2	81	27	81	81	9	9	9	27	27	351	1
4	T3A	81	27	27	27	3	9	81	27	27	309	3
5	T3B	27	27	3	81	3	9	3	27	27	207	7
6	T4	81	27	27	81	3	9	9	27	27	291	5
7	T5	9	27	3	81	3	9	9	27	27	195	8
8	T6A	81	27	27	81	9	9	9	27	27	297	4
9	T6B	81	27	9	81	3	9	9	27	0	246	6
10	T7A	3	27	9	81	9	9	9	27	3	177	12
11	T7B	3	27	9	81	9	9	3	27	3	171	13
12	T7C	9	27	3	81	27	9	3	27	3	189	9
13	T7D	9	27	3	81	27	9	3	27	3	189	9
14	T11A	3	27	9	27	9	9	9	27	3	123	15
15	T11B	3	3	3	27	3	9	3	27	3	81	20
16	T9	3	27	9	27	9	9	3	27	3	117	16
17	T15	3	27	3	9	3	9	3	27	3	87	18
18	T12A	3	9	3	3	3	9	27	27	3	87	18
19	T10	3	27	27	27	3	9	27	27	3	153	14
20	T13	3	27	3	3	3	9	3	27	3	81	20
21	T14A	3	27	9	3	9	9	3	27	3	93	17

Appendix C-3

TABLE 4.1: SUMMARY SHEET OF THE ROCKFALL HAZARD RATING SYSTEM

CATEGORY			RATING CRITERIA AND SCORE			
			POINTS 3	POINTS 9	POINTS 27	POINTS 81
SLOPE HEIGHT			25 FEET	50 FEET	75 FEET	100 FEET
DITCH EFFECTIVENESS			Good catchment	Moderate catchment	Limited catchment	No catchment
AVERAGE VEHICLE RISK			25% of the time	50% of the time	75% of the time	100% of the time
PERCENT OF DECISION SIGHT DISTANCE			Adequate sight distance, 100% of low design value	Moderate sight distance, 80% of low design value	Limited sight distance, 60% of low design value	Very limited sight distance 40% of low design value
ROADWAY WIDTH INCLUDING PAVED SHOULDERS			44 feet	36 feet	28 feet	20 feet
GEOLOGIC CHARACTER	CASE 1	STRUCTURAL CONDITION	Discontinuous joints, favorable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation
		ROCK FRICTION	Rough, Irregular	Undulating	Planar	Clay infilling, or slickensided
	CASE 2	STRUCTURAL CONDITION	Few differential erosion features	Occasional differential erosion features	Many differential erosion features	Major differential erosion features
		DIFFERENCE IN EROSION RATES	Small difference	Moderate difference	Large difference	Extreme difference
BLOCK SIZE VOLUME OF ROCKFALL/EVENT			1 Foot 3 cubic yards	2 Feet 6 cubic yards	3 Feet 9 cubic yards	4 Feet 12 cubic yards
CLIMATE AND PRESENCE OF WATER ON SLOPE			Low to moderate precipitation; no freezing periods; no water on slope	Moderate precipitation or short freezing periods or intermittent water on slope	High precipitation or long freezing periods or continual water on slope	High precipitation and long freezing periods or continual water on slope and long freezing periods
ROCKFALL HISTORY			Few falls	Occasional falls	Many falls	Constant falls

Appendix C-4

Analysis of rockfall hazards

Rockfall Hazard Rating System

Highway and railway construction in mountainous regions presents a special challenge to geologists and geotechnical engineers. This is because the extended length of these projects makes it difficult to obtain sufficient information to permit stability assessments to be carried out for each of the slopes along the route. This means that, except for sections which are identified as particularly critical, most highway slopes tend to be designed on the basis of rather rudimentary geotechnical analyses. Those analyses which are carried out are almost always concerned with the overall stability of the slopes against major sliding or toppling failures which could jeopardise the operation of the highway or railway. It is very rare to find a detailed analysis of rockfall hazards except in heavily populated regions in highly developed countries such as Switzerland.

In recognition of the seriousness of this problem and of the difficulty of carrying out detailed investigations and analyses on the hundreds of kilometres of mountain highway in the western United States and Canada, highway and railway departments have worked on classification schemes which can be carried out by visual inspection and simple calculations. The purpose of these classifications is to identify slopes which are particularly hazardous and which require urgent remedial work or further detailed study.

In terms of rockfall hazard assessment, one of the most widely accepted[4] is the Rockfall Hazard Rating System (RHRS) developed by the Oregon State Highway Division (Pierson et al. 1990). Table 1 gives a summary of the scores for different categories included in the classification while Figure 9 shows a graph which can be used for more refined estimates of category scores.

The curve shown in Figure 9 is calculated from the equation where, in this case, x = (Slope height- feet)/25. Similar curves for other category scores can be calculated from the following values of the exponent x.

Slope height	x = slope height (feet) / 25
Average vehicle risk	x = % time / 25
Sight distance	x = (120 - % Decision sight distance) / 20
Roadway width	x = (52 - Roadway width (feet)) / 8
Block size	x = Block size (feet)
Volume	x = Volume (cu.ft.) / 3

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[4] This system has been adopted by the States of Oregon, Washington, New Mexico and Idaho and, in slightly modified form, by California, Colorado and British Columbia.

Hoek, E. 2007. Practical Rock Engineering. Chapter 9, Analysis of Rockfall Hazards, p. 10-19. rocscience. Online. Accessed October 9, 2019. https://www.rocscience.com/assets/resources/learning/hoek/Practical-Rock-Engineering-Full-Text.pdf

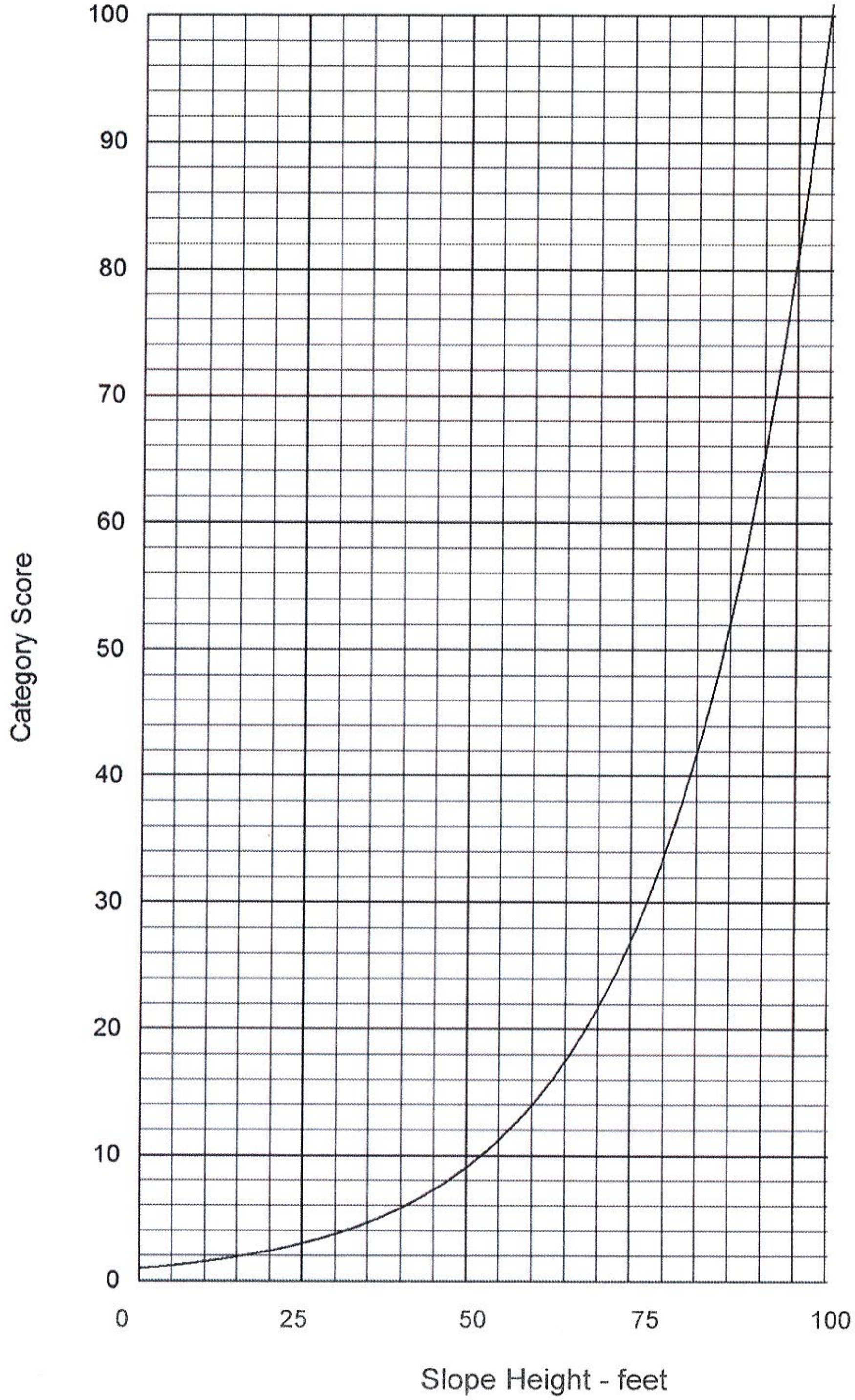


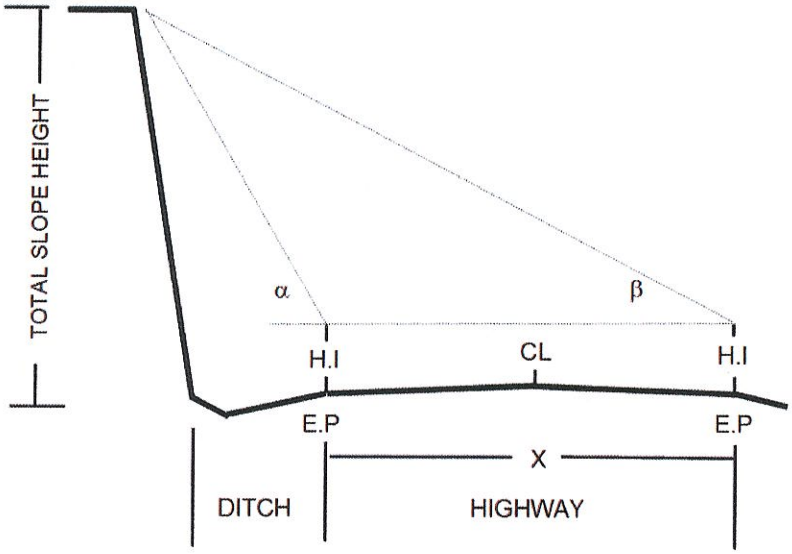
Figure 9: Category score graph for slope height.

Table 1: Rockfall Hazard Rating System.

CATEGORY			RATING CRITERIA AND SCORE			
			POINTS 3	POINTS 9	POINTS 27	POINTS 81
SLOPE HEIGHT			25 FT	50 FT	75 FT	100 FT
DITCH EFFECTIVENESS			Good catchment	Moderate catchment	Limited catchment	No catchment
AVERAGE VEHICLE RISK			25% of the time	50% of the time	75% of the time	100% of the time
PERCENT OF DECISION SIGHT DISTANCE			Adequate site distance, 100% of low design value	Moderate sight distance, 80% of low design value	Limited site distance, 60% of low design value	Very limited sight distance, 40% of low design value
ROADWAY WIDTH INCLUDING PAVED SHOULDERS			44 feet	36 feet	28 feet	20 feet
GEOLOGIC CHARACTER	CASE 1	STRUCTURAL CONDITION	Discontinuous joints, favorable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation
		ROCK FRICTION	Rough, irregular	Undulating	Planar	Clay infilling or slickensided
	CASE 2	STRUCTURAL CONDITION	Few differential erosion features	Occasional erosion features	Many erosion features	Major erosion features
		DIFFERENCE IN EROSION RATES	Small difference	Moderate difference	Large difference	Extreme difference
BLOCK SIZE QUANTITY OF ROCKFALL/EVENT			1 FT 3 cubic yards	2 FT 6 cubic yards	3 FT 9 cubic yards	4 FT 12 cubic yards
CLIMATE AND PRESENCE OF WATER ON SLOPE			Low to moderate precipitation, no freezing periods, no water on slope	Moderate precipitation or short freezing periods or intermittent water on slope	High precipitation or long freezing periods or continual water on slope	High precipitation and long freezing periods or continual water on slope and long freezing periods
ROCKFALL HISTORY			Few falls	Occasional falls	Many falls	Constant falls

Slope Height

This item represents the vertical height of the slope not the slope distance. Rocks on high slopes have more potential energy than rocks on lower slopes, thus they present a greater hazard and receive a higher rating. Measurement is to the highest point from which rockfall is expected. If rocks are coming from the natural slope above the cut, use the cut height plus the additional slope height (vertical distance). A good approximation of vertical slope height can be obtained using the relationships shown below.



$$\text{TOTAL SLOPE HEIGHT} = \frac{(X)\sin\alpha\sin\beta}{\sin(\alpha-\beta)} + \text{H.I}$$

where X = distance between angle measurements
H.I = height of the instrument.

Figure 10: Measurement of slope height.

Ditch Effectiveness

The effectiveness of a ditch is measured by its ability to prevent falling rock from reaching the roadway. In estimating the ditch effectiveness, the rater should consider several factors, such as: 1) slope height and angle; 2) ditch width, depth and shape; 3) anticipated block size and quantity of rockfall; 4) impact of slope irregularities (launching features) on falling rocks. It's especially important for the rater to evaluate the impact of slope irregularities because a launching feature can negate the benefits expected from a fallout area. The rater should first evaluate whether any of the irregularities, natural or man-made, on a slope will launch falling rocks onto the paved roadway. Then based on the number and size of the launching features estimate what portion of the falling rocks will be affected. Valuable information on ditch performance can be obtained from maintenance personnel. Rating points should be assigned as follows:

3 points	*Good Catchment.* All or nearly all of falling rocks are retained in the catch ditch.
9 points	*Moderate Catchment.* Falling rocks occasionally reach the roadway.
27 points	*Limited Catchment.* Falling rocks frequently reach the roadway.
81 points	*No Catchment.* No ditch or ditch is totally ineffective. All or nearly all falling rocks reach the roadway.

Reference should also be made to Figure 8 in evaluating ditch effectiveness.

Average Vehicle Risk (AVR)

This category measures the percentage of time that a vehicle will be present in the rockfall hazard zone. The percentage is obtained by using a formula (shown below) based on slope length, average daily traffic (ADT), and the posted speed limit at the site. A rating of 100% means that on average a car can be expected to be within the hazard section 100% of the time. Care should be taken to measure only the length of a slope where rockfall is a problem. Over estimated lengths will strongly skew the formula results. Where high ADT's or longer slope lengths exist values greater than 100% will result. When this occurs it means that at any particular time more than one car is present within the measured section. The formula used is:

$$\frac{\text{ADT (cars/hour)} \times \text{Slope Length (miles)} \times 100\%}{\text{Posted Speed Limit (miles per hour)}} = \text{AVR}$$

Percent of Decision Sight Distance

The decision sight distance (DSD) is used to determine the length of roadway in feet a driver must have to make a complex or instantaneous decision. The DSD is critical when obstacles on the road are difficult to perceive, or when unexpected or unusual manoeuvres are required. Sight distance is the shortest distance along a roadway that an object of specified height is continuously visible to the driver.

Throughout a rockfall section the sight distance can change appreciably. Horizontal and vertical highway curves along with obstructions such as rock outcrops and roadside vegetation can severely limit a driver's ability to notice a rock in the road. To determine where these impacts are most severe, first drive through the rockfall section from both directions. Decide which direction has the shortest line of sight. Both horizontal and vertical sight distances should be evaluated. Normally an object will be most obscured when it is located just beyond the sharpest part of a curve. Place a six-inch object in that position on the fogline or on the edge of pavement if there is no fogline. The rater then walks along the fogline (edge of pavement) in the opposite direction of traffic flow, measuring the distance it takes for the object to disappear when your eye height is 3.5 ft above the road surface. This is the measured sight distance. The decision sight distance can be determined by the table below. The distances listed represent the low design value. The posted speed limit through the rockfall section should be used.

Posted Speed Limit (mph)	Decision Sight Distance (ft)
30	450
40	600
50	750
60	1,000
70	1.100

These two values can be substituted into the formula below to calculate the 'Percent of Decision Sight Distance.'

Actual Site Distance ( ) x 100% = ______________%
Decision Site Distance (

Roadway Width

This dimension is measured perpendicular to the highway centreline from edge of pavement to edge of pavement. This measurement represents the available manoeuvring room to avoid a rockfall. This measurement should be the minimum width when the roadway width is not consistent.

Geologic Character

The geologic conditions of the slope are evaluated with this category. Case 1 is for slopes where joints, bedding planes, or other discontinuities, are the dominant structural feature of a rock slope. Case 2 is for slopes where differential erosion or oversteepened slopes is the dominant condition that controls rockfall. The rater should use whichever case best fits the slope when doing the evaluation. If both situations are present, both are scored but only the worst case (highest score) is used in the rating.

Case 1

Structural Condition Adverse joint orientation, as it is used here, involves considering such things as rock friction angle, joint filling, and hydrostatic head if water is present. Adverse joints are those that cause block, wedge or toppling failures. 'Continuous' refers to joints greater than 10 feet in length.

3 points	*Discontinuous Joints, Favourable Orientation* Jointed rock with no adversely oriented joints, bedding planes, etc.
9 points	*Discontinuous Joints, Random Orientation* Rock slopes with randomly oriented joints creating a three-dimensional pattern. This type of pattern is likely to have some scattered blocks with adversely oriented joints but no dominant adverse joint pattern is present.
27 points	*Discontinuous Joints, Adverse Orientation* Rock slope exhibits a prominent joint pattern, bedding plane, or other discontinuity, with an adverse orientation. These features have less than 10 feet of continuous length.
81 points	*Continuous Joints, Adverse Orientation* Rock slope exhibits a dominant joint pattern, bedding plane, or other discontinuity, with an adverse orientation and a length of greater than 10 feet.

Rock Friction This parameter directly affects the potential for a block to move relative to another. Friction along a joint, bedding plane or other discontinuity is governed by the macro and micro roughness of a surface. Macro roughness is the degree of undulation of the joint. Micro roughness is the texture of the surface of the joint. In areas where joints contain highly weathered or hydrothermally altered products, where movement has occurred causing slickensides or fault gouge to form, where open joints dominate the slope, or where joints are water filled, the rockfall potential is greater. Noting the failure angles from previous rockfalls on a slope can aid in estimating general rock friction along discontinuities.

3 points	*Rough, Irregular* The surfaces of the joints are rough and the joint planes are irregular enough to cause interlocking. This macro and micro roughness provides an optimal friction situation.
9 points	*Undulating* Also macro and micro rough but without the interlocking ability.
27 points	*Planar* Macro smooth and micro rough joint surfaces. Surface contains no undulations. Friction is derived strictly from the roughness of the rock surface.
81 points	*Clay Infilling or Slickensided* Low friction materials, such as clay and weathered rock, separate the rock surfaces negating any micro or macro roughness of the joint planes. These infilling materials have much lower friction angles than a rock on rock contact. Slickensided joints also have a very low friction angle and belong in this category.

Case 2

Structural Condition This case is used for slopes where differential erosion or oversteepening is the dominant condition that leads to rockfall. Erosion features include oversteepened slopes, unsupported rock units or exposed resistant rocks on a slope that may eventually lead to a rockfall event. Rockfall is caused by a loss of support either locally or throughout the slope. Common slopes that are susceptible to this condition are: layered units containing easily weathered rock that erodes undermining more durable rock; talus slopes; highly variable units such as conglomerates, mudflows, etc. that weather causing resistant rocks and blocks to fall, and rock/soil slopes that weather allowing rocks to fall as the soil matrix material is eroded.

3 points	*Few Differential Erosion Features* Minor differential erosion features that are not distributed throughout the slope.
9 points	*Occasional Erosion Features* Minor differential erosion features that are widely distributed throughout the slope.
27 points	*Many Erosion Features* Differential erosion features are large and numerous throughout the slope.
81 points	*Major Erosion Features* Severe cases such as dangerous erosion-created overhangs; or significantly oversteepened soil/rock slopes or talus slopes.

Difference in Erosion Rates The Rate of Erosion on a Case 2 slope directly relates to the potential for a future rockfall event. As erosion progresses, unsupported or oversteepened slope conditions develop. The impact of the common physical and chemical erosion processes as well as the effects of man's actions should be considered. The degree of hazard caused by erosion and thus the score given this category should reflect how quickly erosion is occurring; the size of rocks, blocks, or units being exposed; the frequency of rockfall events; and the amount of material released during an event.

3 points	*Small Difference* The difference in erosion rates is such that erosion features develop over many years. Slopes that are near equilibrium with their environment are covered by this category.
9 points	*Moderate Difference* The difference in erosion rates is such that erosion features develop over a few years.
27 points	*Large Difference* The difference in erosion rates is such that erosion features develop annually.
81 points	*Extreme Difference* The difference in erosion rates is such that erosion features develop rapidly

Block Size or Quantity of Rockfall Per Event

This measurement should be representative of whichever type of rockfall event is most likely to occur. If individual blocks are typical of the rockfall, the block size should be used for scoring. If a mass of blocks tends to be the dominant type of rockfall, the quantity per event should be used. This can be determined from the maintenance history or estimated from observed conditions when no history is available. This measurement will also be beneficial in determining remedial measures.

Climate and Presence of Water on Slope

Water and freeze/thaw cycles both contribute to the weathering and movement of rock materials. If water is known to flow continually or intermittently from the slope it is rated accordingly. Areas receiving less than 20 inches per year are 'low precipitation areas.' Areas receiving more than 50 inches per year are considered 'high precipitation areas.' The impact of freeze/thaw cycles can be interpreted from knowledge of the freezing conditions and its effects at the site.

The rater should note that the 27-point category is for sites with long freezing periods or water problems such as high precipitation or continually flowing water. The 81-point category is reserved for sites that have both long freezing periods and one of the two extreme water conditions.

Rockfall History

This information is best obtained from the maintenance person responsible for the slope in question. It directly represents the known rockfall activity at the site. There may be no history available at newly constructed sites or where poor documentation practices have been followed and a turnover of personnel has occurred. In these cases, the maintenance cost at a particular site may be the only information that reflects the rockfall activity at that site. This information is an important check on the potential for future rockfalls. If the score you give a section does not compare with the rockfall history, a review should be performed. As a better database of rockfall occurrences is developed, more accurate conclusions for the rockfall potential can be made.

3 points	*Few Falls* - Rockfalls have occurred several times according to historical information but it is not a persistent problem. If rockfall only occurs a few times a year or less, or only during severe storms this category should be used. This category is also used if no rockfall history data is available.
9 points	*Occasional Falls* - Rockfall occurs regularly. Rockfall can be expected several times per year and during most storms.

27 points	*Many Falls* - Typically rockfall occurs frequently during a certain season, such as the winter or spring wet period, or the winter freeze-thaw, etc. This category is for sites where frequent rockfalls occur during a certain season and is not a significant problem during the rest of the year. This category may also be used where severe rockfall events have occurred.
81 points	*Constant Falls* - Rockfalls occur frequently throughout the year. This category is also for sites where severe rockfall events are common.

In addition to scoring the above categories, the rating team should gather enough field information to recommend which rockfall remedial measure is best suited to the rockfall problem. Both total fixes and hazard reduction approaches should be considered. A preliminary cost estimate should be prepared.