within the basement rock, as evidenced by intrusive and extrusive igneous bodies, including pegmatite, rhyolite, dacite, obsidian, and basalt.

The periods of uplift and volcanism, as well as later unloading caused by erosion and mass wasting, created a complex structural condition with highly variable discontinuities, including jointing and faulting, which served as conduits for hydraulic flow and weathering. During the Pleistocene, large scale glaciation carved out drainages and ridgelines, intensifying mass wasting, weathering, and erosion.

As a result of the analysis, several mitigation alternatives were considered. The recommended alternative at the time consisted of a soldier pile wall and ground anchor system. Due to the high cost of this long-term fix, the City elected to realign the existing pipe in the area of the Mudslide and monitor the site along with the remainder of the ditch alignment. A baseline monitoring report of the entire alignment was provided by the consultant in 2013 and annual monitoring reports concerning the condition of the alignment have been submitted thereafter.

In June 2014, the consultants re-visited the Mudslide after increased landslide instability was observed following a wet spring. Inclinometers previously installed were found to be sheared and a lateral scarp sheared through the surface monument of one inclinometer. Surface observations from the site visit as well as recommendations for mitigation and further monitoring were provided to the City. The City again chose to realign the pipeline, re-grade the surface, and continue monitoring the affected portion of the pipeline.

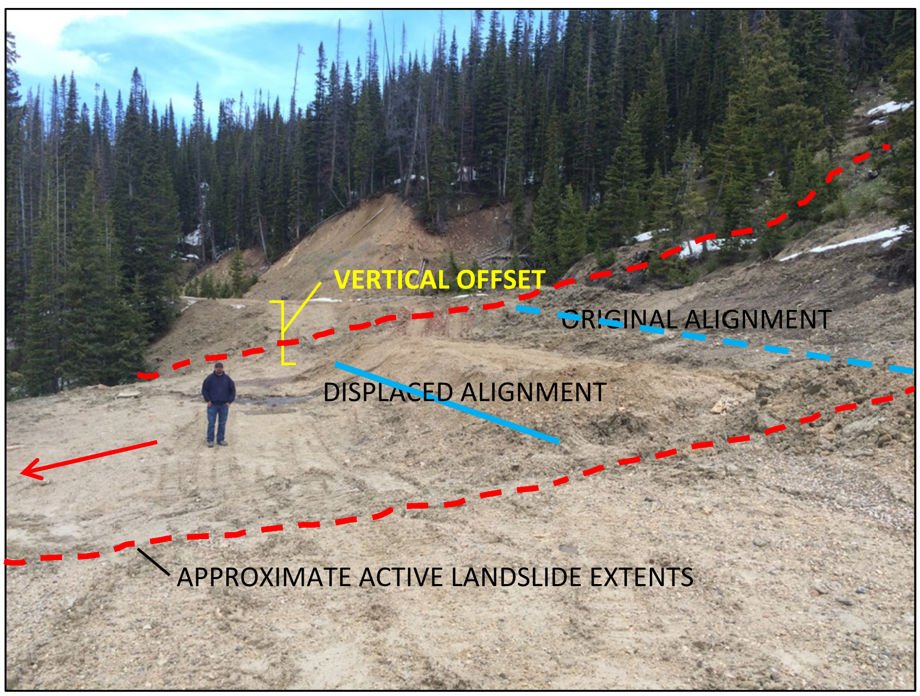

Figure 3: 2015 Displacement caused by Mudslide

During the spring of 2015, significant movement of the Mudslide on the order of 25 ft total took Michigan Ditch offline by rupturing the DIP. Water was diverted upstream of the Mudslide to the natural drainage in order to prevent catastrophic damage to the ditch. The consulting engineers were to identify and evaluate mitigation options. The consultants began a comprehensive geotechnical and subsurface investigation and feasibility study for permanent mitigation of the risk presented by the Mudslide. Figure 3 shows displacement in the roadway paralleling the ditch though the Mudslide.

MITIGATION ALTERNATIVES

Several preliminary mitigation options were considered as long-term solutions for restoring the ditch. The most feasible mitigation options included flexible surface piping (HDPE slide - ultimately removed from consideration due to longevity, maintenance costs, and alignment issues), a bridged aqueduct, tunneling behind the landslide, and landslide stabilization by a combination of soldier piles and tie-backs, as shown in Table 1. Each of these options was evaluated for:

- Initial construction cost;
- Operations and maintenance costs;
- Construction risk and post-construction residual risk, i.e. likelihood of success;
- Access and construction staging;
- Public perception/aesthetics;
- Freeze potential and other operational constraints; and
- Permitting and third party impacts.

Preliminary designs and cost estimates were developed for each option; however, it was necessary to conduct a geological site investigation to refine the designs and cost estimates, and modify assumptions made while evaluating mitigation alternatives and risks.

INVESTIGATIVE TECHNIQUES

The geotechnical investigation techniques chosen were to provide data for multiple mitigation alternatives as well as complement the other techniques' data gaps. Techniques utilized during the investigation included literature review, geologic mapping, vertical test boreholes, horizontal test boreholes, test pits, and seismic refraction.

Geologic mapping and test pits identified bedrock types, landslide composition, better estimated landslide extents, and provided general discontinuity orientations. This complemented other techniques by providing an idea of material types which were encountered later. In addition, this technique affected the layout of the mitigation alternatives. For instance, it was confirmed a foundation for the bridge alternative would be located within the historic landslide. The additional load might reactivate the landslide. Bedrock encountered during mapping and test pitting included granitic gneiss, pegmatite, hornfels, obsidian, and basalt. Surficial deposits included colluvium and glacial till. The surficial deposits were highly weathered and moist fat gray clay with sand, gravel, and woody debris within the landslide extents (Figure 4).

Table 1: Mitigation Alternative Pro/Con Matrix

Option	Relative Costs		Pros & Cons	
	Construction	O&M	Pros	Cons
Bridge Alternative	Neutral	Neutral	• Running water through the structure; efficient with materials • Significant amount of work off-site can be done with onsite assembly • **Does not try to stop the active landslide**	• Challenging design • Other bridge types (suspension, kingpin, etc.) that could overcome constructability issues would be more than 2 times the cost • Stout structure needed to limit sag; which limits freeze risk (solved by camber) • Does not stabilize the ditch road; erecting heavy bridge on active landslide will create challenges • Depth of snow in the area may cause issues from lateral forces from downhill creep as well as plowing operations • Does not appear to be an aesthetically pleasing option to the State Land Board • Aesthetics • Operation and maintenance will require soil removal when/if it builds near and approaches the span • **Difficult to construct while slide is moving** • **Some excavation at toe of landslide may be required, lowering factor of safety for slide stability** • **Does not span the historically mapped slide (one pier located in mapped slide), significant risk of upstream abutment movement if historic slide moves in that area**
Wall	High	Neutral	• Piers are shorter than the "lower wall" option, therefore less cost • Pipe can anchored to the downhill side of the wall to prevent sag and freeze issues	• Expensive • Extremely difficult to construct • Extremely deep piers require large equipment • An excessive amount of spoils • Ditch road is not maintained • Downhill slope may move many feet and expose partial to full height of wall • Aesthetics • Landslides don't like to be stopped; high forces from "locking" it up • **Risk associated with trying to stop a landslide are significant** • **Significant risk of movement during construction as the landslide has not reached equilibrium and likely will never reach a stable condition.**
Tunnel	High	Neutral	• Low maintenance • Very long longevity because in stable bedrock behind the landslide • Aesthetically pleasing (not seen) • Option apparently favored by State Land Board • Geotechnical investigation is robust, allows significant reduction of typical tunneling risks related to unknown ground conditions • Horizontal core acts as a drain to relieve water prior to construction	• Relatively high initial construction cost • Typical risks associated with tunneling such as ground support, groundwater, stuck TBM, etc.

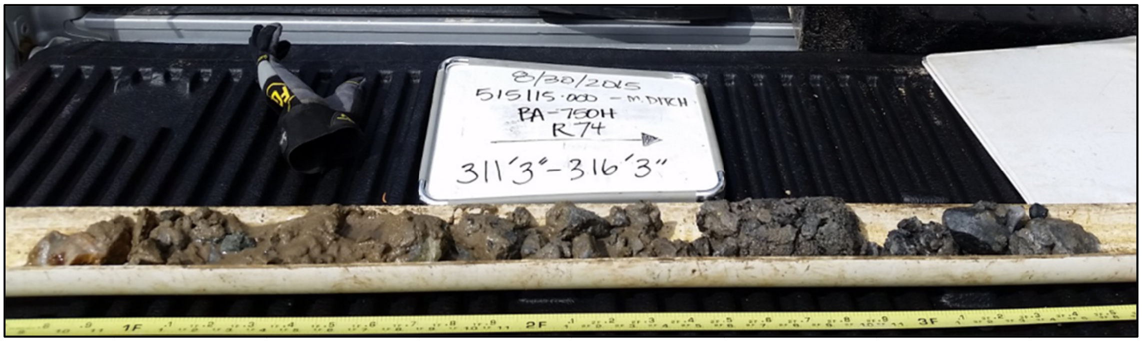

Figure 4: Landslide material encountered in borehole drilling

Vertical boreholes were used to determine the landslide thickness along the road, provide geotechnical data on the rock types and landslide material, estimate geological transitions, and assess foundation characteristics for the bridge and landslide stabilization alternatives. In particular, those alternatives required installing foundations to within stable bedrock and the depth of the foundation affects both cost and stability analyses.

Geophysical seismic refraction techniques estimated depth to bedrock and were utilized after the vertical boreholes were drilled and before the horizontal boreholes were initiated. The vertical boreholes allowed for correlation of the refraction wave velocity to geologic units, namely landslide deposit and bedrock (Figure 5). The seismic refraction survey provided a cross section of materials across the landslide and allowed for positioning of the horizontal boreholes at locations anticipated to be outside of the landslide extents.

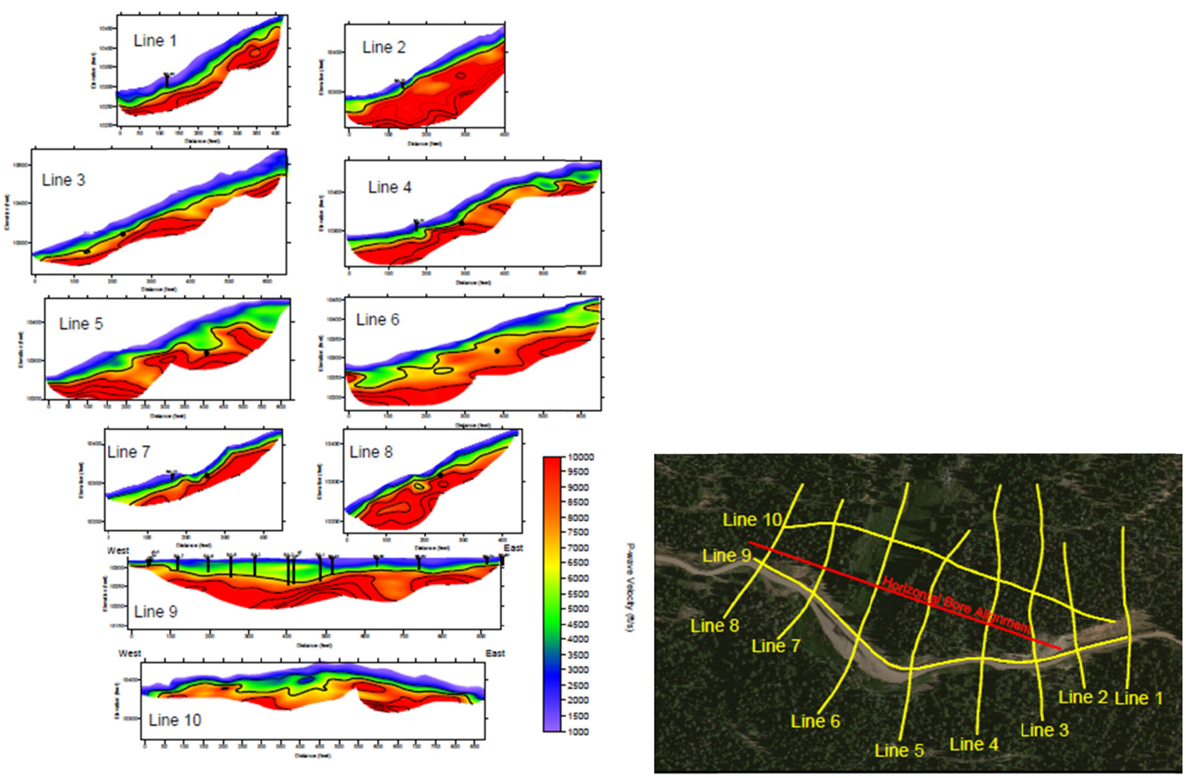

Figure 5: Seismic refraction lines with approximate depth to bedrock (Olson Engineering)

Horizontal boreholes were used to estimate the lateral extent of the landslide and provide geotechnical parameters for the tunnel alternative. If the tunnel alternative was chosen, the ideal alignment would be within competent bedrock, but only so much as necessary to reduce excavation costs and schedule. The horizontal boreholes provided rock quality designation, spacing and orientation of discontinuities, and rough geological transitions. Three horizontal boreholes were drilled near the anticipated tunnel alignment. Two boreholes encountered landslide material at depths greater than expected; thus, the anticipated tunnel alignment was modified. The third borehole confirmed the modified alignment was outside of the landslide. The material encountered is generally characterized by highly fractured (RQD 0 % - 30 %), hard bedrock (UCS up to 10,000 psi) with frequent zones of highly weathered sandy and gravely clay infilling. The compiled data is presented in Figure 6.

Overall, the geotechnical investigation yielded approximate geometry of the landslide and provided geotechnical design data for the mitigation alternatives. As a result of the investigation, a Multi-Criteria Decision Analysis was conducted (Table 2). The HDPE slide, landslide stabilization wall and suspension bridge alternatives resulted in low ratings, primarily due to limited or unknown longevity. Landslide stabilization carried post-construction risk as activation of sympathetic slope failures is possible. The bridge alternative and site logistics required locating a foundation on historic landslide, which also carried post-construction risk. The HDPE slide was ruled out due to anchoring requirements, maintenance costs, and alignment concerns.

SELECTED MITIGATION AND CONSTRUCTION

Ultimately, the longevity and engineering feasibility of the tunnel alternative proved desirable as a long-term solution to the Mudslide landslide problem. The tunnel had high initial construction cost, but low risk of post-construction failures and minimal third party impacts. In addition, the geotechnical investigation both confirmed the feasibility of the alternative and provided suitable information to begin design. The data obtained during the investigation were summarized in a geotechnical summary report provided to the City.

Due to the project schedule, the City was able to expedite design and construction with a collaborative effort by several contractors and consultants. Once the ditch access road was cleared of snow in May 2016, a contractor widened portions of the access road and prepared a tunnel entry and exit location. A purpose-built, 96-inch diameter Akkerman tunnel boring machine (TBM) was launched in June 2016 on a curved alignment through bedrock behind the landslide. The machine is propelled by hydraulic cylinders off the initial support, which consists of steel ribs at 4-ft spacing and timber lagging (Figure 7). The cutterhead was designed to excavate through both highly fractured hard rock and highly weathered soft rock. The TBM is nearing the completion point of the tunnel as of mid-September 2016.

Since the tunnel is on a curved alignment, the apex of the tunnel is further from the intersection of the boreholes. Consequently, more intact and less weathered bedrock were encountered than indicated in the horizontal boreholes. Excavation proved more difficult than expected due to bedrock encountered, cutterhead design and unfavorable joint orientations, but the alignment is expected to be completed prior to winter snowfall closing the site.

Table 2: Multi-Criteria Decision Analysis for Selected Mitigation Alternatives

Option	Cost[1]					
	Construction	Contingency (Percent)	Contingency (Dollars)	Project Management	Engineering	Total Cost
Weighted score[3]						
Wall	$ 5,900,000	10%	$ 590,000	$ 300,000	$ 1,180,000	$ 7,970,000
Bridge Alternative	$ 3,200,000	25%	$ 800,000	$ 300,000	$ 800,000	$ 5,100,000
Tunnel	$ 5,000,000	20%	$ 1,000,000	$ 300,000	$ 750,000	$ 7,050,000

Option	Risk[2]						Score[4] (out of 10)
	Cost[5]	O&M[2]	Construction	Longevity	Public Perception	Permit Feasibility	
Weighted score[3]	3	0.5	2	3	1	0.5	10
Wall	1	2	1	2	2.5	1	**3.00**
Bridge Alternative	3	2	2	2	2.5	2	**4.70**
Tunnel	1	2	3	5	5	5	**6.50**

Notes:

1 Costs are entered as whole dollars; the 'Total Cost' sums all the individual cost inputs
2 Values for O&M and Risk for each option are assigned a value (or ranked) on a scale of 1 to 5, one (1) being very unfavorable and five (5) being the most favorable
3 The 'Weighted Score' row (dark blue) assigns a subjective value of each column/category, the sum of all the columns should equal a score of ten (10)
4 The score tally on the right hand column computes based on the cost, input values, and assigned weighted values; the high scores are the most favorable options; the low scores are the least favorable options.
5 The following cost ranges and associated weighting factors were assigned based on the total estimated cost of the project

5 - < $1,000,000
4 - > $1,000,000 and < $3,000,000
3 - > $3,000,000 and < $5,500,000
2 - > $5,500,000 and < $7,000,000
1 - > $7,000,000

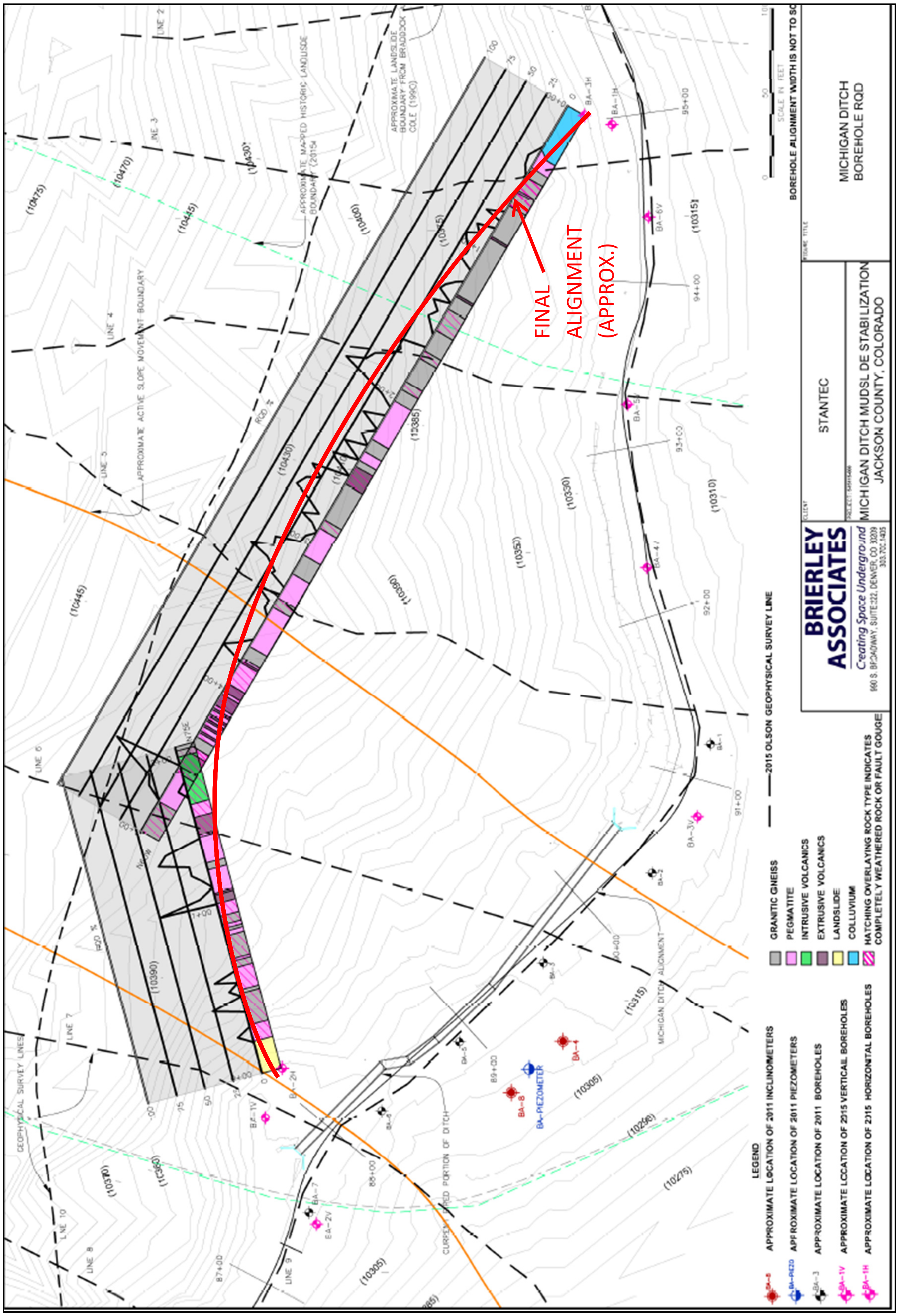

Figure 6: Investigation layout and bedrock/RQD encountered along boreholes

Figure 7: The TBM heading. Muck conveyor removed.

CONCLUSION

The geotechnical investigative techniques chosen for the Michigan Ditch Mudslide allowed for evaluation of various mitigation alternatives and provided valuable geotechnical data for selected design. Geologic mapping and test pits provided an overall picture of the hazard and representative materials. Vertical boreholes and geophysical refraction survey provided an estimate of landslide thickness and extent. Horizontal boreholes provided localized landslide margins, material types, discontinuity information, and rock quality designation. All of these parameters affected alternative design and identified weaknesses and residual risks which may be present post-construction. Largely influenced by the results of the geotechnical investigation, the Mudslide landslide problem is to be mitigated by a tunnel through competent bedrock behind the landslide. Once the tunnel is completed, the water will resume flow within the Michigan Ditch traveling along its new alignment behind the landslide.

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Probabilistic Back Analysis Based on Polynomial Chaos Expansion for Rainfall-Induced Soil Slope Failure

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Abstract

In probabilistic back analysis for rainfall-induced slope failure, the computational load is usually demanding due to time-consuming numerical deterministic model. In this paper, a polynomial chaos expansion (PCE)-based MCMC simulation is proposed to accelerate the probabilistic back analysis. A surrogate model based on PCE is used to substitute the coupled hydro-mechanical model of an unsaturated soil slope under rainfall infiltration. The coefficients in the PCE surrogate model are estimated using the spectral projection method with the Gauss-Hermite (GH) sparse grid. The posterior inferences of soil parameters are obtained using the Markov Chain Monte Carlo (MCMC) simulation. The results of an example show that the proposed method is computationally faster and more efficient than the traditional approach in exploring the posterior parameter distributions.

INTRODUCTION

The in situ soil parameters are difficult to estimate and poorly known a priori due to natural variability and measurement errors in the field. This limitation promotes the use of back analysis methods which can estimate soil properties based on observed measurements. In recent years, Bayesian approaches are becoming increasingly popular in probabilistic back estimation (e.g., Oliver et al. 1997; Efendiev et al. 2005; Zhang et al. 2010). However, the deterministic models used in back estimation are usually computationally demanding. For the stability of a soil slope under rainfall infiltration, a coupled hydro-mechanical numerical model should be used for simulation of the coupled behavior of water flow and stress-deformation. Therefore, the probabilistic back analysis becomes a daunting task with such a complicated model.

In this study, an efficient method is proposed for probabilistic back analysis of soil slope failure under rainfall infiltration. This method adopts the Polynomial Chaos Expansion (PCE) method (Wiener 1938) to establish a surrogate model, which is used to substitute the coupled hydro-mechanical numerical deterministic model of slope stability. The posterior distributions of soil parameters are obtained using the Markov Chain Monte Carlo (MCMC) simulation based on the Bayesian theory. With the integration of the surrogate model and the MCMC simulation, the probabilistic back analysis of soil slope under rainfall infiltration is accelerated. The efficiency and accuracy of the proposed method are illustrated using an example.

METHODOLOGY

Surrogate model based on Polynomial Chaos Expansion

To build the coupled hydro-mechanical model of an unsaturated soil slope under rainfall infiltration, the Bishop's effective stress for unsaturated soil and the elasto-plastic model with the Mohr-Coulomb yield criterion were adopted utilizing finite element program ABAQUS. Consider that the input parameters are standard Gaussian random variables, which is represented by a vector $\boldsymbol{\theta} = (\theta_1,\ldots,\theta_n)$. The Polynomial Chaos Expansion (PCE) approximation of the output $g(\boldsymbol{\theta})$ of the coupled hydro-mechanical model can be expressed by (Soize and Ghanem 2004)

$$g(\boldsymbol{\theta}) = \sum_{i=1}^{P-1} a_i \boldsymbol{\Psi}_i(\boldsymbol{\theta}) \tag{1}$$

where a_i are unknown expansion coefficients and $\boldsymbol{\Psi}_i(\boldsymbol{\theta})$ are the products of multivariate orthogonal polynomials for expansion terms $i = 1,\ldots,P$. P denotes the total number of n-dimensional orthogonal polynomials $\boldsymbol{\Psi}_i(\boldsymbol{\theta})$ of degree not exceeding the highest polynomial degree U. To construct the PCE surrogate model of the coupled hydro-mechanical model, the highest polynomial degree $U = 2$ is applied herein taking account of computation effort and correlation between the different parameters.

The coefficients in the PCE surrogate model are estimated using the spectral projection method with the Gauss-Hermite (GH) sparse grid. In the use of the spectral projection framework, a crucial issue is how to choose the nodal set $\{\boldsymbol{\theta}_j, w_j\}$. Sparse grid collocation (Gerstner 2003) can drastically reduce the sampling points number and preserve a high accuracy. The collocation sampling of sparse grid method is in the independent standard normal space. Sparse grids with sets $\boldsymbol{\theta}_j$ of equidistant knots is adopted based on Gauss-Hermite rules in this paper. The expansion coefficients a_i in the orthogonal PCE are calculated using spectral projection method (Xiu 2007)

$$a_i = \frac{\sum_{j=1}^{Q} g(\boldsymbol{\theta}_j)\boldsymbol{\Psi}_i(\boldsymbol{\theta}_j) w_j}{\left\langle \boldsymbol{\Psi}_i^2(\boldsymbol{\theta}) \right\rangle} \tag{2}$$