World Academy of Science, Engineering and Technology
International Journal of Structural and Construction Engineering
Vol:18, No:1, 2024

Open Science Index, Structural and Construction Engineering Vol:18, No:1, 2024 publications.waset.org/10013476.pdf

Case-Based Reasoning Application to Predict Geological Features at Site C Dam Construction Project

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Abstract**—**The Site C Hydroelectric dam is currently being constructed in north-eastern British Columbia on sub-horizontal sedimentary strata that dip approximately 15 meters from one bank of the Peace River to the other. More than 615 pressure sensors (Vibrating Wire Piezometers) have been installed on bedding planes (BPs) since construction began, with over 80 more planned before project completion. These pressure measurements are essential to monitor the stability of the rock foundation during and after construction and for dam safety purposes. BPs are identified by their clay gouge infilling, which varies in thickness from less than 1 to 20 mm and can be challenging to identify as the core drilling process often disturbs or washes away the gouge material. Without the use of depth predictions from nearby boreholes, stratigraphic markers, and downhole geophysical data, it is difficult to confidently identify BP targets for the sensors. In this paper, a Case-Based Reasoning (CBR) method was used to develop an empirical model called the Bedding Plane Elevation Prediction (BPEP) to help geologists and geotechnical engineers to predict geological features and BPs at new locations in a fast and accurate manner. To develop CBR, a database was developed based on 64 pressure sensors already installed on key bedding planes BP25, BP28, and BP31 on the Right Bank, including BP elevations and coordinates. 13 (20%) of the most recent cases were selected to validate and evaluate the accuracy of the developed model, while the similarity was defined as the distance between previous cases and recent cases to predict the depth of significant BPs. The average difference between actual BP elevations and predicted elevations for above BPs was ± 55 cm, while the actual results showed that 69% of predicted elevations were within ± 79 cm of actual BP elevations while 100% of predicted elevations for new cases were within ± 99 cm range. Eventually, the actual results will be used to develop the database and improve BPEP to perform as a learning machine to predict more accurate BP elevations for future sensor installations.

Keywords**—**Case-Based Reasoning, CBR, geological feature, geology, piezometer, pressure sensor, core logging, dam construction.

I. INTRODUCTION

THE Site C Hydroelectric project is a 1,100 Megawatt (MW) hydroelectric earthfill dam project currently being constructed on the Peace River in British Columbia, Canada. Site C is the third dam in the Peace River hydroelectric system. Between the 1970s and the start of construction in 2015, extensive geotechnical investigations of the dam site were conducted. During construction, detailed geological mapping of large bedrock excavations and borehole logging with modern geophysical methods have been completed. The geological features observed at the site closely align with the Valley Stress relief theory developed by [1]-[6] including the main features of steeply dipping extensional joints, bedding parallel shearing, and cross cutting shears in the base of the valley.

Bedding Planes (BPs) are identified by their clay gouge infilling and can be challenging to identify in drill core as the drilling process often disturbs or washes away the gouge material. Without the use of depth predictions from nearby boreholes, stratigraphic markers, and down hole geophysical data it can be nearly impossible to confidently identify BP targets for pressure sensors (Vibrating Wire Piezometers). In fact, it is very important to identify the correct BPs through core logging to install the sensors to monitor pore water pressure for geotechnical purposes.

More than 615 pressure sensors have been installed on BPs and other geological features since construction began, with over 80 more planned before project completion. To help geologists and geotechnical engineers to predict BP elevations in advance, CBR as an Artificial Intelligence (AI) method was used to develop an empirical model called Bedding Plane Elevation Prediction (BPEP) to consider input data and produce reliable results in a short period of time [7].

II. CASE-BASED REASONING

A. Methodology

CBR is a problem-solving strategy that uses previous cases to solve new problems [8]-[10]. These methods have been derived from a Genetic Algorithm presented by John Holland in 1975 [11]. CBR has been developed as an expert system by Schank and Ableson in 1977 [12]. It has a range of applications in various design problems: in manufacturing process design [13], in building and mechanical design [14], [15], in material science [16], [17], in fault diagnosis [18], in medical planning [19] and in knowledge modelling [20]. At the highest level of generality, a general CBR cycle may be described by the following four processes [21]-[23]:

- RETRIEVE the most similar case or cases
- REUSE the information and knowledge in that case to

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solve the problem

- REVISE the proposed solution
- RETAIN the parts of this experience likely to be useful for future problem solving

This cycle is illustrated in Fig. 1. In this paper, CBR has been used to make an empirical model to predict BP elevations at Site C.

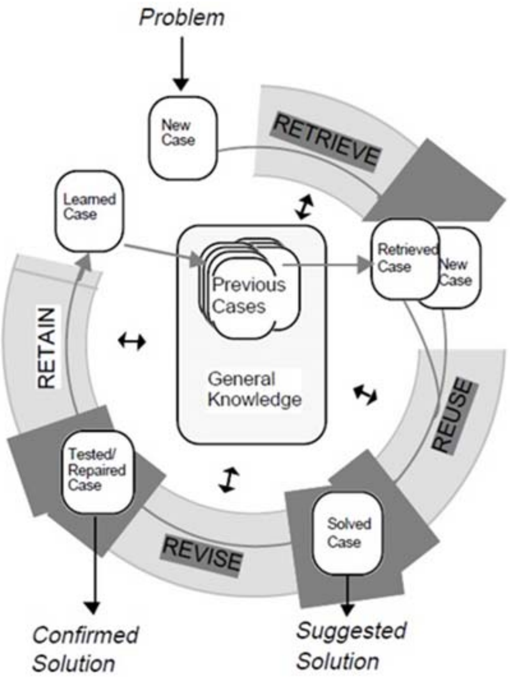

Fig. 1 CBR cycle [23]

B. Database Development

Case storage is an important aspect of designing CBR methods. In fact, it should reflect the conceptual view of what is represented in the case and consider case characteristics. On the other hand, the main knowledge source for a CBR system is a database of previously solved problems and their solutions [24]. Therefore, more cases in the database will lead to higher chance to retrieve case or cases with higher similarity to the new case. In this paper, previously installed sensors including coordinates and targeted BP elevations have been used for each case wherein actual BP elevations were selected and stored in database as a result of each case [25]. Each case was developed based on features extracted from several BPs identified through borehole logging.

Table I shows an example about how the database was developed for all cases.

TABLE I
DATABASE CREATED FOR BPEP

Case number	BP	Piezometer ID	Northing	Easting	Actual BP Elevation (Results)
1	*BP25*	*PVW_RCC-G2*	*6229251.05*	*629281.58*	*412.33*
2	*BP28*	*PVW_RCC-G2*	*6229251.05*	*629281.58*	*401.82*
⋮	⋮	⋮	⋮	⋮	⋮
i	BP_i	P_i	N_i	E_i	El_i

C. Retrieve Procedure

The computation of similarity is an important issue for the case retrieving process in CBR [26]. An appropriate similarity function needs to be developed to handle the hidden relationships between the objects associated with cases [27], [28]. Therefore, after making the database, a procedure should be developed to retrieve the case which has highest similarity to the new case. In this paper, the distance between the new case (Cn) and previous cases was selected to calculate the similarity. Equation (1) shows how the similarity can be calculated:

$$Sim(BP_n)=100\times(1-(D_{n-i}/D_{max})) \tag{1}$$

where $Sim(BP_n)$: Similarity between new case (C_n) and case i (C_i) if the BP_n is same as BP_i; BP_n: BP for the new case (C_n); BP_i: BP for case i (C_i); D_{max}: Maximum distance between new case (C_n) and all cases recorded in database; D_{n-i}: Distance between new case and Case i.

Equation (2) shows how to calculate D_{n-i}:

$$D_{n-i}=((N_n-N_i)^2+(E_n-E_i)^2)^{0.5} \tag{2}$$

where N_n: Northing coordinate of new case (C_n); N_i: Northing coordinate of case i (C_i) – refer to Table I; E_n: Easting coordinate of new case (C_n); E_i: Easting coordinate of case i (C_i) – refer to Table I.

Based on (1), similarity ($Sim(BP_n)$) will be 100% when there is already a case in database in the exact location as the new case while the similarity will be Zero between the furthest case and the new case while all considered cases have the same BP as BP_n. On the other hand, the similarity between Cn and Ci should be calculated only when the BP_i is same as BP_n.

Eventually, after calculating similarity between the new case and all stored cases, the most similar case can be retrieved from the stored cases with its BP elevation as a prediction for the new case.

D. Making CBR Intelligent

To make CBR intelligent, all new cases with their actual BP elevations should be stored in the database after the actual BP elevation is identified for C_n. This procedure should be repeated for all new cases to increase the accuracy of CBR dynamically, and consequently make its results more reliable.

III. SITE C DAM CONSTRUCTION

The Site C clean energy is one of the largest hydroelectric infrastructure projects in Canada located seven kilometers southwest of Fort St John in British Columbia, Canada. The dam and hydroelectric generating station on the Peace River in northeast British Columbia will provide 1100 MW of capacity and produce about 5100 Gigawatt-hour (GWh) of electricity each year, enough energy to power the equivalent of 450,000 homes per year in British Columbia. Fig. 2 shows a final overview of Site C Dam after completion [29].

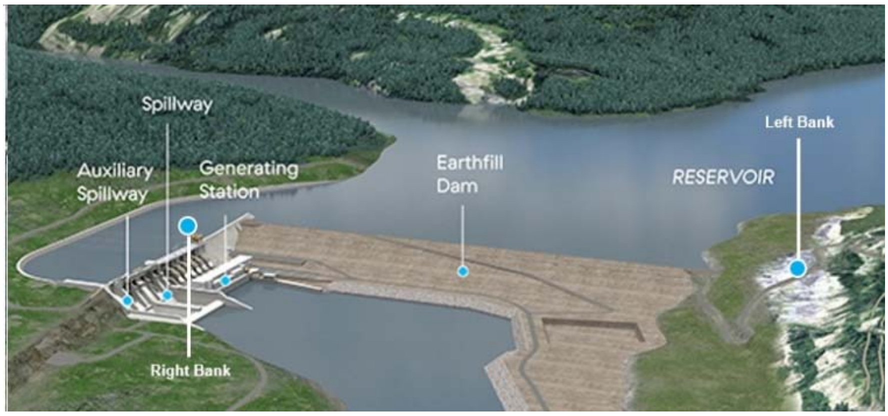

Fig. 2 A plan view of Site C project [29]

A. Site C Geology

The site is located in a broad U-shaped valley approximately 180 to 230 m deep and several kilometers wide [30]. It is underlain by the Lower Cretaceous age rocks of the Shaftesbury Formation, part of the Fort St John Group. The Shaftesbury Formation consists of flat laying shales, siltstones, and sandstones, and is locally dominated by silty shales with shale, siltstone, and sandstone interbeds. At the site, the bedding dips at 1° to 2° degrees to the northwest and causes the stratigraphy to drop approximately 15 m across the site.

The current Peace River Valley formed by rapid incision from late Wisconsonian Laurentide deglaciation meltwaters [31]. The stress relief from valley incision produced BPs, cross cutting shears and steeply dipping extensional joint sets in the valley walls. The geologic features observed at the site align closely to the work completed by Ferguson and Hamel, and Matheson in similar valley environments [1]-[5].

BPs identified in the stratigraphy have been numbered sequentially from the top down at the site. Amongst the many BPs that have been identified, only a handful of them are continuous across the entire site at the same stratigraphic elevation. The continuous BPs typically have < 1 to 20 mm of clay gouge infilling (Fig. 3), have residual shear strengths as low as 8° [30], and are significantly weaker than the intact rock. The BPs represent a potential instability surface in the dam foundation and pressure sensors (Vibrating Wire Piezometers) have been installed throughout these features to measure pore water pressure during construction and over the lifespan of the dam. For this study location, the elevation data from piezometer holes that target significant BPs in the base of the valley (BP25, BP28 and BP31) have been selected for use in the CBR model (Fig. 4). Table II shows the actual elevation range of these BPs in the right bank.

Fig. 3 BP25 with approximately 20 mm of clay gouge infilling

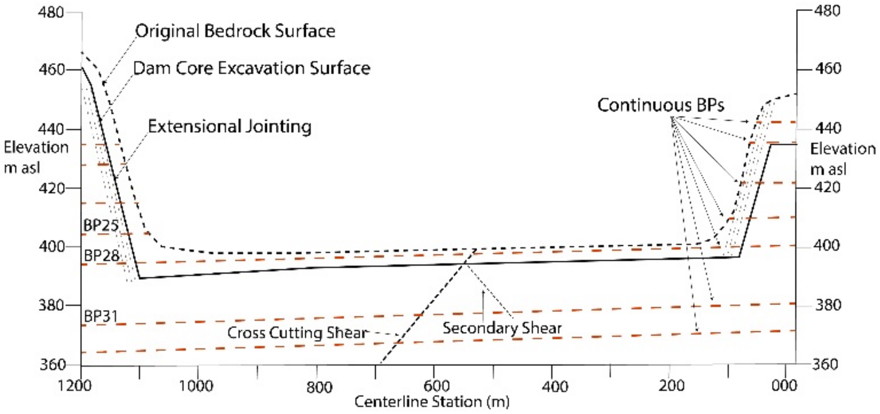

Fig. 4 5X vertical exaggeration cross section of main dam excavation, looking downstream

B. Validate BPEP at Site C Project

To validate BPEP, a database was developed based on 64 pressure sensors that have been installed at BP25, BP28 and BP31 on the right bank including BP elevations, borehole coordinates, and Piezometer IDs. Of the 64 piezometers installed at the BPs, 20% (13 cases) of most recent piezometers were selected to validate and evaluate the resultant accuracy of BPEP while the similarity was defined as the distance between previous cases and recent cases to predict the depth of the significant BPs.

TABLE II
ACTUAL IDENTIFIED ELEVATIONS FOR BP25, BP28, AND BP28 AT RIGHT BANK OF PEACE RIVER AT SITE C

BP	Actual Identified Elevations (m)		Average (m)	Difference Between Min and Max El. (m)
	Minimum	Maximum		
BP25	*412.13*	*415.96*	*414.15*	*3.63*
BP28	*401.23*	*405.33*	*403.78*	*4.10*
BP31	*385.99*	*387.56*	*386.69*	*1.57*

There are a total of 21 piezometers installed at BP25 on the right bank of the river and 20% (4 cases) of most recent piezometers were selected to predict BP25 elevations and validate BPEP. The average results showed that predicted elevations for BP25 for last four cases were accurate to ± 70 cm while 75% of results were accurate to ± 79 cm BPEP Error distributions for predicted BP25 elevation results provided in Fig. 5.

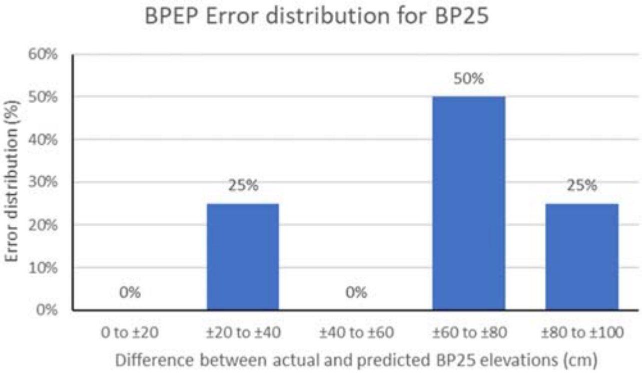

Fig. 5 The Error distribution based on differences between predicted and actual elevations for BP25

For BP28, 36 piezometers have been installed at Right Bank and 20% (7 cases) of most recent piezometers were selected to predict BP28 elevations and validate BPEP. The average results showed that predicted elevations for BP28 were accurate to ± 57 cm while 29% of results were accurate to ± 9 cm and 57% of results accurate to ± 66 cm. BPEP Error distributions for predicted BP28 elevation results are provided in Fig. 6.

BP31 was the next BP considered for BPEP validation. In this case, 7 piezometers have been installed on the right bank of the river and 20% (two cases) of most recent piezometers were selected to predict BP31 elevations and validate BPEP. The average results showed that predicted elevations for BP28 were accurate to ± 20 cm and 100% of results were as accurate as ± 25 cm. BPEP Error distributions for predicted BP31 elevation results are provided in Fig. 7.

Generally, BPEP Error distribution calculated for all BP25, BP28 and BP31 at Right Bank and results showed that 69% of predicted elevations for above BPs were within the range of ± 79 cm when compared to actual BP elevations. The average Error in this case was ± 55 cm. Fig. 8 shows the Error distribution of all selected cases for BP25, BP28 and BP31.

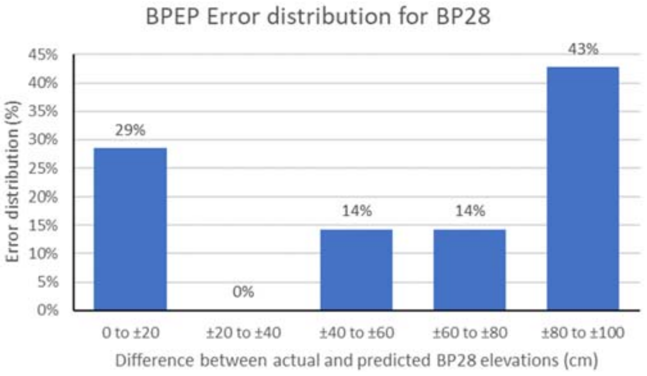

Fig. 6 The Error distribution based on differences between predicted and actual elevations for BP28

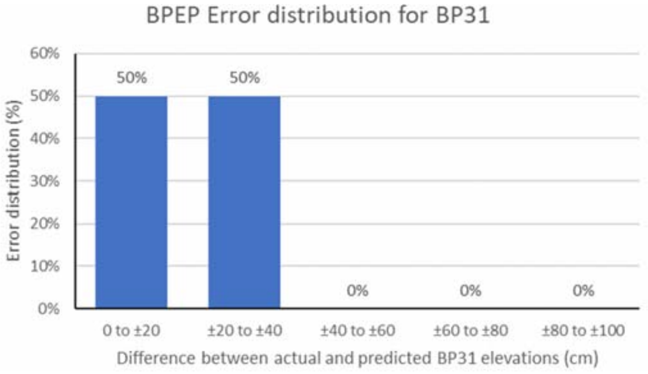

Fig. 7 The Error distribution based on differences between predicted and actual elevations for BP31

BPEP was also able to identify the closest installed piezometers to the new cases to help geologists and geotechnical engineers to expedite the process of finding the nearby previous borehole logs and consequently its BP elevations.

All 13 selected new cases were eventually added to database to improve the number of actual cases in CBR database and make BPEP even more knowledgeable.

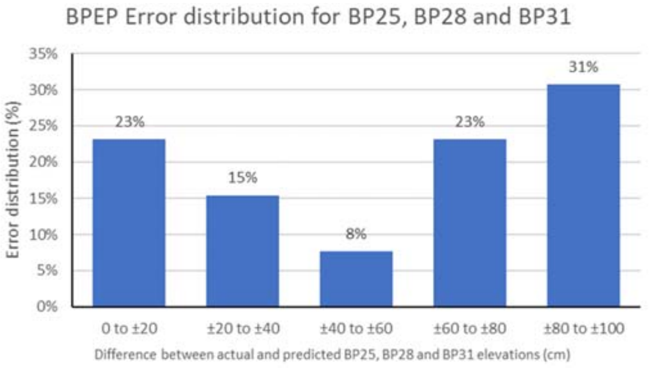

Fig. 8 The Error distribution based on differences between predicted and actual elevations for BP25, BP28 and BP31

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IV. CONCLUSION

BPEP is an intelligent model developed based on CBR method to predict BP elevations at Site C. Its database was developed by considering important features such as previous borehole coordinates, piezometer IDs and the actual BP elevations as a result of each case. By using BPEP, the most similar case was easily retrieved from its database to predict the BP elevation of the new cases.

The BPEP was validated for 13 selected most recent cases out of 64 existing cases and the BP25, BP28 and BP31 were predicted accordingly by calculating the similarity. The average difference between actual BP elevations and predicted elevations for above mentioned BPs was less than ± 55 cm while the actual results showed that 69% of predicted elevations were within ± 79 cm range of actual BP elevations. It should also be considered that BPEP predicted the BP elevations within ± 20 cm accuracy for 23% of cases.

In fact, considering the wide range of actual identified BP elevations at Site C (Table II), the BPEP average errors proves that this model is providing accurate prediction for geological features.

Eventually, the actual BP elevations for 13 selected cases and their features such as the Piezometer IDs, borehole coordinates and BP elevations will be added to database and used to improve the accuracy of future BP elevation predictions and improve BPEP database to act as a learning machine.

Error distribution can be improved as more cases with their actual results are added to database to make BPEP more knowledgeable. In addition, it should be also considered that the geologists may not always be able to identify the actual BP in drill core or geophysical logs which may cause installing the piezometer at wrong depth and/or elevation. This can affect the accuracy of BPEP results as the input data are not reflecting the reality.

On the other hand, the accuracy of input data will affect the accuracy of BPEP, However, BPEP accuracy can be improved when more cases with correct real results are being added during the time. Mapping data can also be added to database to improve BPEP results.

Currently, beside borehole logging and geophysical techniques, BPEP is being used at Site C to help geologists and geotechnical engineers to identify BP elevations in advance for future Piezometer installation purposes.

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