Performance Measures
Numerical Modeling of the Test Pit for Falling Weight Deflectometer Calibration

Evaluation of pavement sections is commonly conducted using the deflection data from Falling Weight Deflectometer (FWD) tests. The reliability of these evaluations is highly dependent on the accuracy of the measured deflections. Therefore, to ensure the desired accuracy of measured deflections, FWDs undergo annual calibration and monthly relative calibrations. These calibrations are conducted according to AASHTO-R32-11. The calibration tests are conducted on an indoor test pit made of a concrete slab underlaid by a base and a soft subgrade.

The calibration facility operated by the Montana Department of Transportation (MDT) has used a 12 ft wide, 15 ft long, and 5 in thick concrete slab overlying a 6-in thick sandy base and a 4-ft thick clay subgrade (R32 design). The measured deflections during calibration tests conducted by MDT on this test pit met the deflection requirements laid out by AASHTO-R32-11 for a few years, after which the test area needed to be replaced. Because rebuilding the test area is both costly and time-consuming, the MDT was interested in a new design that could operate over longer periods. MDT designed an alternative to the R32 design, using geofoam instead of the clay layer as the soft subgrade.

An alternative calibration test pit (alternative geofoam test pit) was designed based on static analyses. The designed test area was constructed, and several FWD calibration tests were conducted. The new setup did not meet all the AASHTO-R32-11 deflection requirements. Also, some deflections (noise) upon initiation of the falling weight (before the weight actually hits the plate) were detected by the accelerometers during the calibration tests conducted on the geofoam test pit. Therefore, the MDT sponsored a research project to investigate the possibility of using geofoam instead of the clay layer in the test pit based on dynamic response analyses.

To do this a three-dimensional explicit finite volume model was developed using FLAC3D (Itasca) software (developed by Itasca Consulting Group, Inc., Minneapolis, Minnesota, USA). In this stage, the measured data during the calibration tests conducted by the MDT was used to validate the developed model. In the next step, the model was modified and used to simulate the behavior of the alternative geofoam test pit. After validating the model for both the original clay setup and the alternative geofoam setup, the model was used to design new geofoam setups that meet the AASHTO-R32-11 requirements. Thirty different designs were proposed in this stage that satisfied the deflection requirements. The differences between the designs were in terms of geometry and dimensions of the layers and the type of geofoam used in the setup, i.e., geofoam EPS 19 vs. geofoam EPS 29. The proposed designs were ranked based on five criteria, i.e., AASHTO's maximum deflection requirements, reducing the noise observed in the alternative geofoam setup, proper damping, construction cost, and variability (the possible deviation between the designed material properties and as-built material properties). After all the designs were ranked based on the criteria, the three best designs were proposed to the MDT.

To conduct the cost-benefit analyses for using the proposed geofoam designs instead of calibrating offsite or using the R32 design, the following assumptions and considerations were made:

1. The R32 test pit has to be reconstructed every few years due to its short service time. The reconstruction not only takes a lot of time and effort but also costs more than $10,000 every time.
2. The cost to calibrate the FWDs offsite was $12,000 in 2019 ($5,000 for calibrating two FWDs and $7,000 for transportation). This price was somewhat affected by the global pandemic (COVID19) and the consequent travel restrictions. However, it is estimated that the cost of calibration for MDT without the calibration test pit would be around $9,000 per year.
3. The MDT plans to test the proposed design full scale to verify the performance of the design. However, once the proposed design is finalized, other entities can also use it for their FWD calibration tests in the country which will reduce their costs of removing and reconstructing their test pits. Also, with the higher durability that the new design is provided with, there will be a decrease in the maintenance costs for the clients.

Calculations:

Given the fact that the research started in 2020 at a cost of $33,210, the equation below was used to convert the cost to the present value:

- $Present\ value\ of\ research\ cost = P * (1+s)^n * (1+r)^n$

Where: P = initial cost of research, r is the discount rate, n is the number of years, and s is the inflation rate. Therefore, the present value of the research cost in 2021 is:

$$Present\ value\ of\ research\ cost = \$33{,}210 * (1+0.03)^1 * (1+0.03)^1 = \$35{,}232.40$$

The following equations were used to determine the present discounted value of future benefits, benefit to cost ratio, and return on investment (ROI) respectively for 20 years.

- $Present\ discounted\ value\ of\ future\ benefits = Benefit = \sum_{n=0}^{t} \frac{Q}{(1+r)^n}$

Where: Q is the estimated savings per year, and t is the total number of years over which these savings will be calculated.

- $Benefit\ to\ cost\ ratio = \frac{Benefit}{Cost}$
- $Return\ on\ investment\ (ROI) = \frac{(Gain\ on\ Investment - Cost\ of\ investment)}{Cost\ of\ investment}$

Table 1 demonstrates the annual costs of FWD calibration over 20 years considering three different alternatives. The first column of the table shows the annual costs without a calibration facility, the second column shows the annual costs when using the R32 design and the third column shows the annual costs when using the proposed geofoam design. It is worth noting that although we expect the geofoam layer to last longer than the clay layer, for cost-benefit calculations we assumed that the concrete slab still needs to be replaced every four years with an approximate cost of $4,000.

Table 1. Annual costs of the potential alternatives

Year	Do Nothing (Calibration offsite)	Replace with R32 Design	Replace with Geofoam Design
1	$9,000	$10,000	$10,000
2	$9,000		
3	$9,000		
4	$9,000	$10,000	
5	$9,000		$4,000*
6	$9,000		
7	$9,000	$10,000	
8	$9,000		
9	$9,000		$10,000
10	$9,000	$10,000	
11	$9,000		
12	$9,000		
13	$9,000	$10,000	$4,000*
14	$9,000		
15	$9,000		
16	$9,000	$10,000	
17	$9,000		$10,000
18	$9,000		
19	$9,000	$10,000	
20	$9,000		
Total	**$180,000**	**$70,000**	**$38,000**

*The cost of replacing the concrete slab.

The following equation was used to calculate the amount of savings per year for different scenarios:

- $The\ annual\ savings = \frac{Total\ costs\ in\ alternative\ a - Total\ costs\ in\ alternaive\ b}{Number\ of\ years}$

Using the equation above, the amount of savings per year when using the R32 design compared to calibrating offsite was calculated to be $5,500. The amount of savings per year when using the proposed geofoam design compared to calibrating offsite is $7,100. Finally, the amount of savings per year is $1,600 when using the proposed geofoam design compared to the R32 design.

Using the calculated annual savings, the present discounted values of future benefits, the benefit to cost ratio, and the return on investment (ROI) are calculable for the three scenarios:

1. When using the R32 design compared to calibrating offsite, the amount of savings over 20 years would be \$5,500 per year, therefore:

$$Present\ discounted\ value\ of\ future\ benefits = Benefit = \sum_{n=0}^{20} \frac{\$5500}{(1+0.03)^n} = \$81{,}826.10$$

$$The\ benefit\ to\ cost\ ratio = \frac{\$81{,}826.10}{\$35{,}232.40} = 2.32$$

$$Return\ on\ investment\ (ROI) = \frac{(\$81{,}826.10 - \$35{,}232.40)}{\$35{,}232.40} = 1.32$$

2. When using the proposed geofoam design compared to calibrating offsite, the amount of savings over 20 years would be \$7100 per year, therefore:

$$Present\ discounted\ value\ of\ future\ benefits = Benefit = \sum_{n=0}^{20} \frac{\$7{,}100}{(1+0.03)^n} = \$105{,}630.10$$

$$The\ benefit\ to\ cost\ ratio = \frac{\$105{,}630.10}{\$35{,}232.40} = 2.99$$

$$Return\ on\ investment\ (ROI) = \frac{(\$105{,}630.10 - \$35{,}232.40)}{\$35{,}232.40} = 1.99$$

3. When using the proposed geofoam design compared to the R32 design, the amount of savings over 20 years would be \$1,600 per year, therefore:

$$Present\ discounted\ value\ of\ future\ benefits = Benefit = \sum_{n=0}^{20} \frac{\$1{,}600}{(1+0.03)^n} = \$23{,}803.96$$

$$The\ benefit\ to\ cost\ ratio = \frac{\$23{,}803.96}{\$35{,}232.40} = 0.67$$

$$Return\ on\ investment\ (ROI) = \frac{(\$23{,}803.96 - \$35{,}232.40)}{\$35{,}232.40} = -0.32$$

Comparing the benefit to cost ratio and the ROI of scenarios 1 and 2, the geofoam setup has the highest potential for cost-saving. The ROI of the third scenario, comparing the R32 design to the geofoam design, is negative due to the cost of this research. It is worth mentioning, however, that there are eight calibration facilities in the US. If only one other facility adopts the geofoam design, the benefit would increase by twofold to \$47,607.92. In that case, the benefit to cost ratio and ROI would improve to:

$$The\ benefit\ to\ cost\ ratio = \frac{\$47{,}607.92}{\$35{,}232.40} = 1.35$$

$$Return\ on\ investment\ (ROI) = \frac{(\$47{,}607.92 - \$35{,}232.40)}{\$35{,}232.40} = 0.35$$

Obviously, the more facilities adopt the geofoam design, the higher benefit to cost ratio and ROI are achieved. In the best-case scenario, for example, if all the other facilities adopt the geofoam design, the benefit would increase by eightfold to $190,431.68. In that case, the benefit to cost ratio and ROI would be:

$$The\ benefit\ to\ cost\ ratio = \frac{\$190431.68}{\$35{,}232.40} = 5.4$$

$$Return\ on\ investment\ (ROI) = \frac{(\$190431.68 - \$35{,}232.40)}{\$35{,}232.40} = 4.4$$

Therefore, even though the return on investment for the MDT is negative due to the cost of this research, there is a national positive effect on the FWD user community if geofoam can be implemented into their calibration facilities.

It is also worth noting that the proposed geofoam setup needs to be constructed and tested by the MDT. Moreover, it is still unknown that how long the geofoam will actually last under the repeated impacts of the falling weight. It was assumed here that the geofoam layer needs to be replaced every eight years but the concrete slab should be replaced every four years. The cost-benefit analyses provided here, therefore, might change according to the actual performance of the geofoam test pit.