PREDICTION OF DAMAGE POTENTIAL ON ALASKAN HIGHWAYS
DURING SPRING THAW USING THE FALLING WEIGHT DEFLECTOMETER

FINAL REPORT

by

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ABSTRACT

Benkelman Beam data has been widely used to design overlays and establish load restrictions. However, research carried out in Alaska has shown that gross errors can occur from its use in areas where freeze-thaw conditions prevail. It has long been known that the shape of the deflection basin is related to the life of the pavement. As a result, a method has been developed to determine the damage potential and thaw depth based on Falling Weight Deflectometer (FWD) tests. This method adjusts the measured center deflection to the deflection which would have been obtained had no frozen materials been present in the pavement structure. This adjusted FWD deflection is essentially equivalent to the traditional Benkelman Beam deflection (for relatively thin asphalt-surfaced pavements, at the same test load) so that conventional methods may be used to design overlays and establish load restrictions.
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INTRODUCTION

In areas where cyclic freeze-thaw conditions prevail, it is very important to establish the structural integrity of flexible pavements during periods of "thaw weakening" which, in Alaska, generally occur between the initiation of thaw in the upper pavement layers and when the thaw depth has progressed to some 5 - 10 feet.
In Alaska, where the depth of frost penetration can be appreciable indeed and the thawing process relatively long, this period of time can extend into weeks or even months. Based on experience, it has been found that load limits as large as 50% are necessary on many primary state routes anywhere from initial thawing until the thaw depth has reached several feet. Since this can place very extensive and costly restraints on the transportation industry in particular—and therefore society in general—it was important to find a non-destructive test method which would more accurately pinpoint: a) whether a given section of roadway is, in fact, weakened during periods of thawing; b) if so, during what period of time are load limits necessary and; c) the level of load restriction required.

Pavement damage has been regularly observed before Benkleman Beam deflections indicate significantly large deflections suggesting that total deflection alone may be inadequate in establishing load restrictions. It is reasonable to assume that even small deflections over a very weak base and a frozen subgrade are more damaging than large deflections over a stronger base and thawed subgrade, since the conditions for dramatic or total failure in the base is indicated by, e.g., the excessively high vertical base strains under the load. An example of such a failure can be seen in Figure 1.
FIGURE 1: Pavement Failure
To fill this need, a method has been developed using the Dynatest Model 8000 Falling Weight Deflectometer (FWD) Test System which is capable of ascertaining the extent of structural weakening of the pavement system for any thaw depth between a few inches and over 10 feet. The method involves collecting FWD data and processing this data through a computer program called "FROST". The program uses the load and seven deflection (basin) values measured at each test point with the FWD to ascertain:

1) the approximate thaw depth;

2) the "corrected" center deflection for a 9,000 pound equivalent half-axle load, had there been no frozen materials in the pavement structure, adjusted to a surface temperature of 70° F.;

3) a "damage indicator," corresponding to the approximate resilient vertical strain in the granular base material, under the design 9,000 pound load.

The proposed method allows the engineer to monitor the structural adequacy of the pavement at any time during the spring thaw period. Such monitoring is expected to reduce and possibly eliminate, through rehabilitation of candidate pavements, the need for load limits in Alaska, which are very costly to the Alaskan economy.

THE NEED FOR LOAD RESTRICTIONS

In Interior Alaska, asphalt surfaced pavements are typically frozen to a depth in excess of 10 feet for some 5 months per year. It has been generally concluded that no significant load-associated pavement deterioration takes place during this period of time. Indeed, deflection measurements taken in the completely frozen state show only very minute deflections (<<0.001" for either a standard Benkelman Beam test or a comparable 9000 lb. FWD test).
Traditionally, pavement deflections have been monitored in Alaska throughout the "spring thaw" period. Based on these, load restrictions have been applied for periods of time starting when Benkelman or FWD measurements reflect a significant increase in deflection until after the deflections have reached their peak value [1]. This procedure has been helpful in preventing unacceptably rapid pavement deterioration due to heavy loads, but it is strongly felt that a more accurate method of assessing the need for load restrictions should be sought because it has been shown that each day of load restrictions on the Alaska statewide road network costs the trucking industry approximately $100,000 (1980 dollars) [1].

THAWING PAVEMENT SECTIONS

a) Completely Thawed Condition

A pavement section in an unfrozen state may be modeled as shown in Figure 2A. Under load, the pavement will deflect according to the theory of elasticity, the magnitude of each deflection along the deflection basin being dependent on the elastic properties of the materials in the section.

The deflections measured furthest from the load roughly reflect the condition of subgrade, because the compression of the pavement layers above the subgrade is negligible compared to the vertical movement of the subgrade itself [2]. The center deflection, on the other hand, may be thought of as the sum of the vertical strains throughout each layer from the top downwards and is therefore affected by all layers.
Figure 2A: Schematic representation of an unfrozen asphalt surfaced pavement under a 9,000 lb. load.

Figure 2B: Schematic representation of the same section in a partially frozen (thaw depth ≈ 6") state under a 9000 lb. load.
b) Partially Thawed Condition

The same pavement section depicted in Figure 2A is shown in a partially frozen state in Figure 2B, after the thaw has progressed to a depth of some 6" below the asphalt layer. It can be seen that the magnitude of the center deflection is only about 1/3 of the value of the corresponding unfrozen system center deflection. Nevertheless, a comparative analysis of these two companion pavement sections using the Chevron N-layered computer program reveals that the horizontal strain at the underside of the asphalt and the vertical strain at the top of the base are approximately equal, despite the dramatic difference in deflection. Thus the center deflection alone is a poor indicator of the potential for pavement distress.

The asphalt strain (in the present example, some 400-500μ in/in.), though, is still not critical due to the thin surface involved (approximately 1½"), while the magnitude of vertical strain in the base is very high (≈2,600 x 10^-6), just below the asphalt-base interface. A good indicator, therefore, of the structural integrity of an asphalt pavement section during spring thaw-weakened periods is the vertical strain in the granular base. This is due to the very large resilient strains in the base apparently give rise to base shear failure which is, of course, propagated through the thin asphalt surface prior to asphalt fatigue failure per se.

DEFLECTION MEASUREMENTS

It should be obvious from the preceding that the center deflection reading is not necessarily indicative of a pavement's potential for load-associated distress, unless perhaps the depth of thaw is known and an adjustment in the measured value is carried out. Generally, the thaw depth will vary greatly from point to point, depending on the exposure of the pavement to sunlight, the type of materials present, water content, etc. Even an approximate thaw depth based on nearby frost tube measurements can be off several feet and thus by a factor of 2 or more in terms of adjusted (unthawed) center deflection.
The acquisition in the spring of 1982 by the State of Alaska of a heavy load capacity Dynatest Falling Weight Deflectometer has now made it possible to conduct load-deflection measurements using a standard equivalent wheel load of 9,000 pounds rapidly. The requisite deflection basin readings necessary to determine the thaw depth and damage potential at any given test point are also obtained. At a test spacing of 0.2 miles, 200 or more test points per day can be covered by a single operator. Thus at least 40 miles of roadway can be inventoried in a single work day. The State of Alaska's FWD is shown in Figure 3.

Generally, each selected roadway is surveyed at least once a week in order to observe the changing structural conditions over the typical spring thaw period of 3-6 weeks.

FIGURE 3: Falling Weight Deflectometer
INTERPRETATION OF FWD LOAD-DEFLECTION DATA

a) The FWD Configuration

The FWD load-deflection configuration is variable, both in terms of the load radius, the magnitude of the applied load and the deflection measurement positions. The loading plate is circular, with a hole in its center for measurement of the center deflection, and six other available deflection sensing transducers may be positioned as desired from just outside the loading plate to a distance of some 2.25 meters (approximately 7') along the raise/lower bar (see Figure 4).

Due to the relatively thin asphalt-surfaced pavements prevalent in Alaska, it was deemed appropriate to utilize a relatively close sensor configuration, as follows:

\[
\begin{array}{cccccccc}
& 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
Distance from center of load (mm) & 0 & 200 & 300 & 450 & 650 & 900 & 1200 \\
(in) & 0 & 7.9 & 11.8 & 17.7 & 25.6 & 35.4 & 47.2
\end{array}
\]

FIGURE 4

A 300 mm (=12") loading plate is used, which results in a pressure level of about 82 psi at the design 9,000 lb. wheel load. This corresponds with normally encountered truck tire loadings. Other features of the FWD have been described elsewhere [3,4].

In accordance with the theoretical effect of frozen materials on the deflection basin as shown in Figures 2A and 2B, it was immediately noticed that the same tendency towards virtually no deflection at large distances from the FWD load was occurring during the early spring of 1982. Such a phenomenon can only occur if the underlying layers have a very high stiffness or modulus of elasticity. It was thus decided to utilize layered elastic theory to ascertain what the effects of thaw depth and other material characteristics would have on the seven FWD deflections.
b) Selection of Input Parameters

Since the FWD is non-destructive, only the FWD test load and deflections, and perhaps some information of the likely range of layer thicknesses from construction records were readily accessible. A series of Chevron N-layer program runs was made, using the likely range of conditions present in Alaskan roadways, as follows:

- Thaw depth (below asphalt): 50 mm - 4200 mm (2" - 14')
- Thickness of Layer 1 (AC): 20 mm - 75mm (3/4" - 3")
- E-value (stiffness) of Layer 1: 3000 - 6000 MPa (430,000 - 870,000 psi)
- Thickness of Layer 2 (granular base): 300 mm (12")
- E-value of Layer 2 (thawed portion): 25 - 450 MPa (3,500 - 65,000 psi)
- Thickness of Layer 3 (subbase/embankment): 1500 mm (59")
- E-value of Layer 3 (thawed portion): 75 - 150 MPa (11,000 - 22,000 psi)
- Thickness of Layer 4 (original soil): semi-infinite
- E-value of Layer 4 (thawed portion): 50 - 100 MPa (7,000 - 15,000 psi)
- E-value of all frozen material: 10,000 MPa (1,500,000 psi)

A thaw depth of 4200 mm (14') was considered the equivalent of a thawed (or deep permafrost) section, since the effect of the modulus of the materials below a depth of 14' under a 9,000 pound load is negligible.

c) Processing of Input Parameters

Using various combinations within the range of parameters listed above, while eliminating some very unlikely combinations, about 350 Chevron computer runs were executed. As a result, a "solution table" was created, each line consisting of:

1) The specific combination of input parameters (i.e., layer thicknesses, thaw depth, etc.) associated with the output.
2) The vertical surface deflections (i.e., the deflection basin) for a 9,000 pound FWD applied load.

3) The vertical strain at the surface of the thawed portion of the granular base.

4) The horizontal strain at the underside of the asphalt-bound surface course.

Two examples of deflection basins were figuratively shown in the preceding (Figures 2A and 2B). In Figure 2B, it can clearly be seen how the deflection values rapidly approach zero as the distance from the load increases, for a pavement having a shallow thaw depth. The early spring FWD data gathered showed precisely the same tendency which dictated the next step: compare the FWD field-gathered data with the solution table data and find the best fit, or fits.

THE FROST PROGRAM

a) The Best Fit

The FROST program was written in BASIC, adaptable both for the HP-85 micro-computer, provided with the FWD by the manufacturer, and for the main frame Honeywell computer currently used by the Alaska Department of Transportation and Public Facilities.

The program first scales the FWD-measured deflection basin to the 9,000 pound design load since the measured FWD load varies perhaps between 8,500 and 9,500 pounds. It then scans the solution table comparing the theoretical set of deflection basins with the measured one, and selects the three "best fit" theoretical basins from the solution table. The best fit is based on a derived solution index or "score" as described in the following paragraph. Each of the three are finally weighted in proportion to their "goodness of fit" to determine the required output parameters.
The "score" is determined partially on the basis of the absolute value of the difference between each theoretical (i.e., from the solution table), and measured deflection (in μm) and partially from the offset of the measured deflections from lying parallel to the theoretical deflection basin. The two offsets for each deflection position, i.e. the absolute offset and offset from being parallel, are linearly weighted in proportion to their distance from the center of the loading plate [in mm] (except the center deflection, which was arbitrarily assigned a weight of 50).

This is done in order to weigh more heavily the outermost sensors since these deflection readings are affected to the greatest degree by the presence of frozen materials in the pavement structure.

Thus the lowest score represents the best fit. The three lowest scores from the measured deflection basin vs. the solution table basins are weighted proportionally to the inverse square of their scores. The output parameters are determined through this weighted averaging technique.

This may be mathematically represented as:

\[
\frac{3}{\sum_{i=1}^{3} \frac{D_i}{(l_i)^2}}\]

\[
\frac{3}{\sum_{i=1}^{3} \frac{1}{(l_i)^2}}\]

where \(D_i\) = an unknown parameter (e.g., the depth of thaw)
for each of the three "best fit" solution table data sets i.

and \(l_i\) = the "score" of the three respective "best fit" data sets i.
For example, if the three best fit curves had scores of 4,000, 6,500 and 20,100 respectively, and their corresponding solution table thaw depths were 6”, 3” and 12” in that order, the program would calculate a thaw depth of:

\[
\frac{6}{(4,000)^2} + \frac{3}{(6,500)^2} + \frac{12}{(20,100)^2} = 5.37”
\]

As discussed in the following section, it is recognized that this is at best an approximation, so the FROST program would print out an approximate frost depth of between 3” and 9”.

b) The FROST Output

The three theoretical deflection basins selected by the FROST program are associated with their own unique values of thaw depth, E values, layer thicknesses, etc. Since the solution table does not cover every conceivable solution due to the unmanageably huge matrix of possible solutions, only an approximation of the results can be expected for each individual output parameter.

It was therefore decided that the most indicative and direct parameters in the FROST output would be:

1) The approximate thaw depth. Since the FROST program heavily weighs the outermost deflections, this parameter can be fairly easily determined to within approximately one foot at shallow thaw depths and two feet or so at greater depths.
2) The adjusted center deflection. The solution table also predicts what the deflection would have been had no frost been present in the upper approximately 14' of materials, all other parameters being equal. This adjusted, "no frost" deflection value is further adjusted for temperature to a standard 70°F using the following equation [5]:

\[ d_{1, \text{adj}. 70^\circ} = d_{1, \text{adj.}} (0.64 + 25.2/t) \] (1)

where:

- \( d_{1, \text{adj}. 70^\circ} \) = deflection adjusted to 70°F
- \( d_{1, \text{adj.}} \) = adjusted field measured deflection
- \( t \) = pavement temperature (°F)

This equation was found to be sufficiently accurate for the 3" or less of asphalt thicknesses involved.

3) The "damage indicator". This is a value which is really tantamount to the theoretical vertical strain at the top of the granular base (under the load). This was deemed at the outset to be the most indicative measure of load-damage potential for springtime, thawing conditions.

c) Example

An example of the FROST program output is shown in Figure 5. The example was taken from springtime measurements taken along the Parks Highway connecting Anchorage and Fairbanks, Alaska. Note that the input quantities are in metric units derived from the FWD tests, while the output has been converted to standard American units for the user's convenience.
Figure 5

Input File: PH#2

Date: 82 04 26 Temp: 66 F.
Roadway: PARKS HIGHWAY; RUN#2
Load Radius (mm): 150
Sensor Positions (mm):
0 200 300 450 650 900 1200

Station: 292b
Load-adjusted deflections [μm]:
632 433 306 178 74 16 0
Approx.thaw depth: 3 - 5 ft
Thawed, adj.center deflection = 29.0 mils [@ 70 F]
Damage factor = 1600 μ in/in
[Approx.vertical stain in base]

Station: 292.2b
Load-adjusted deflections [μm]:
1174 717 429 159 17 1 1
Approx.thaw depth: 2 - 3 ft
Thawed, adj.center deflection = 56.4 mils [@ 70 F]
Damage factor = 3900 μ in/in
[Approx.vertical stain in base]

Station: 292.4b
Load-adjusted deflections [μm]:
933 531 241 66 4 1 1
Approx.thaw depth: 2 - 3 ft
Thawed, adj.center deflection = 42.3 mils [@ 70 F]
Damage factor = 2700 μ in/in
[Approx.vertical stain in base]

Station: 292.6b
Load-adjusted deflections [μm]:
854 551 338 121 51 17 7
Approx.thaw depth: 3 - 5 ft
Thawed, adj.center deflection = 37.3 mils [@ 70 F]
Damage factor = 2300 μ in/in
[Approx.vertical stain in base]

Station: 292.8b
Load-adjusted deflections [μm]:
636 386 223 101 39 17 9
Approx.thaw depth: 3 - 5 ft
Thawed, adj.center deflection = 28.4 mils [@ 70 F]
Damage factor = 1600 μ in/in
[Approx.vertical stain in base]

Station: 293b
Load-adjusted deflections [μm]:
604 376 216 92 33 13 8
Approx.thaw depth: 3 - 5 ft
Thawed, adj.center deflection = 27.1 mils [@ 70 F]
Damage factor = 1400 μ in/in
[Approx.vertical stain in base]
Figure 6 compares the actual measured deflection with the adjusted deflection at a typical FWD test point as a function of test data. The vertical strain on the base is also plotted for the same test point in Figure 7. A plot of horizontal asphalt strain also shows the same tendency, namely that the largest strains (and therefore damage potential) often occur prior to the peak, unadjusted deflection. Also, the peak adjusted deflection follows both the horizontal asphalt strain as well as the vertical base strain, so any of these parameters may be used as an indicator of damage potential.

In the example shown, the greatest damage potential actually occurred on the same data as the lowest center deflection, which would result in gross errors in the establishment of load restrictions.

In Figure 8, it can be seen how the FROST program calculates the increase on thaw depth as a function of time.

APPLICATION OF THE FROST PROGRAM

The establishment of load restrictions has traditionally been based on the judgement of the maintenance foreman and the Benkelman Beam deflection measurements. In 1980, a method of establishing load restrictions was adopted which attempted to limit damage during spring thaw to that expected during the summer months. (1) Analysis of the data collected by the Falling Weight Deflectometer showed that this objective was not being accomplished. This was further supported by maintenance personnel who felt the adopted method placed load restrictions too late. However, it proved to correctly indicate when to remove load restrictions.

The method developed in 1980 was based on Figure 9. Knowing the normal summer deflection and the deflection measured in the spring, the load restriction could be found. Using Figures 6 and 9 and assuming the normal summer deflection is 0.015 in., a 75% load limit was placed about April 26 under the current method. By using the adjusted deflection from Figure 6 and Figure 9, 50% load restrictions should have been enforced prior to March 23. Field investigations showed the 75% load restrictions were inadequate for this section since much of the pavement was severely fatigue cracked within the first week of spring thaw.
Figure 6: Comparison of Actual and Adjusted Deflections

- Deflections (mils)
- O = Adjusted Deflection
- △ = Actual Deflection

Figure 7: Vertical Strain in Base

- Vertical Strain in Base (μ/ln)
- Date: 4/23, 4/26, 5/3, 5/10
Figure 8: Predicted Thaw Depth
By using the adjusted center deflection from the FROST program, load restrictions may be imposed from the time the greatest damage potential along a section of roadway approaches the limiting value of the curves in Figure 9 [1]. After the adjusted deflections once again fall below the threshold value, the load restrictions may once again be lifted.

The greatest value of this method, however, is the ability of the FWD and FROST program to quickly and accurately delineate the sections of roadway most in need of structural rehabilitation. In many cases, it appears that only short lengths of roadway over very long distances need imminent repair, so it is hoped that some well-placed maintenance and repair funds will eventually eliminate the need for load restrictions on all primary state routes.

LIMITATIONS OF THE PROGRAM

The range of solution table parameters used in the FROST program was solely geared for Alaskan roadways. It is recognized that other cold-climate applications of the method reported herein will require an additional range of parameters (e.g., larger asphalt thicknesses) to enhance the limited range covered by the present solution table.

SUMMARY AND CONCLUSIONS

Load restrictions have traditionally been based on Benkelman Beam data collected during the spring-thaw period. However, it has been shown that the shape of the deflection basin significantly affects the pavement life. Use of the Falling Weight Deflectometer and the Chevron 5 Layer computer program model has shown that the maximum damage potential may occur long before the peak deflection occurs.

A method has been developed to adjust the measured center FWD deflection so that the adjusted deflection can be used to design overlays and establish load restrictions in a conventional manner. The center deflection is then adjusted using the shape of the deflection basin to
FIGURE 9
LOAD LIMIT PERCENTAGES
GIVEN MEASURED DEFLECTIONS
AND THE NORMAL SUMMER DEFLECTION LEVELS
OR ACCEPTABLE DEFLECTION LEVELS

% of 18,000 lb. AXLE LOADING ALLOWED

100 %
80 %
60 %
40 %
20 %

50 % Load Limit
75 % Load Limit
Normal Summer Deflection Levels
Or Acceptable Deflection Levels

MAXIMUM MEASURED DEFLECTION

0.020 0.030 0.040 0.050 0.060 0.070 0.080 0.090
determine the deflection that would have occurred in a completely thawed embankment. It is felt that this adjusted deflection is a better indicator of the damage potential to highway surfaces in areas where thaw-weakening occurs.

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