LINKING GRANULAR BASE/SUBBASE RESIDUAL DEFORMATIONS IN NAPTF PAVEMENT TEST SECTIONS TO TRANSVERSE RUT PROFILES

Phillip Donovan – P.E., Ph.D.
Ph: (217) 333-6975 / E-mail: phillip.donovan@kunsan.af.mil

and

Dr. Erol Tutumluer – Professor
(Corresponding Author) / Ph: (217) 333-8637
E-mail: tutumlue@illinois.edu / (Fax: 217-333-1924)

Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
205 North Mathews, Urbana, IL 61801

PRESENTED FOR THE
2010 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Atlantic City, New Jersey, USA

April 2010

ABSTRACT

This paper presents findings from a recent research study focused on the analysis of the behavior of unbound aggregates to offset wheel loads at the FAA's Center of Excellence for Airport Technology (CEAT) established at the University of Illinois. Test data from full-scale aircraft gear loading conducted at the FAA's National Airport Pavement Test Facility (NAPTF) were used to investigate the effects of wander (offset loads) on the deformation behavior of unbound aggregate layers in asphalt pavement test sections. The overall objective was to develop a better understanding of the complex rebound (recovered) and residual (unrecovered) deformation trends of granular materials due to passing of each of the 6-wheel B777 type and the 4-wheel B747 type gears for various combinations of applied load magnitudes and loading sequences (stress history effects), traffic directions, and wander positions and sequences.

The NAPTF rutting performance data for the CC1 flexible pavement test sections were gathered for transverse pavement surface profiles and the individual deformations in the P209/P154 granular base/subbase layers indicated by the Multi-Depth Deflectometer (MDD) data. The unique analyses of the MDD data pioneered the use of critical transverse profile points and critical point multiplication factors to calculate individual pass residual transverse profiles. It then combined the individual profiles through an entire wander pattern to simulate the actual applied traffic on NAPTF sections and determine the creation of the residual deformation basin and the final transverse profile.

INTRODUCTION

The Federal Aviation Administration (FAA) has been conducting full-scale New Generation Aircraft (NGA) tests since 2000. The tests are conducted at the National Airport Pavement Test Facility (NAPTF) located at the William J. Hughes Technical Center close to the Atlantic City International Airport. The NAPTF was built to analyze the effects of NGA on pavements. The tests use a specially designed test vehicle that can apply loads of up to 75 kips (333.6 kN) per wheel on two landing gear carriages with up to ten wheels per carriage. Wheel loads are programmable along the travel lanes and the lateral positions (wander) of the landing gears are variable up to plus or minus 60 in. (1,524 mm) from the nominal travel lanes to simulate aircraft wander.

The first series of tests conducted were referred to as Construction Cycle 1 (CC1) tests. The Boeing 777 (B777) type landing gear tested in the North lane was a six-wheel dual-tridem configuration with dual wheel spacing of 54 in. (1,372 mm) and tridem axle spacing of 57 in. (1,448 mm). The wheel loads were set to 45 kips (200.2 kN) and the tire pressure was set to 188 psi (1.3 MPa). The complete six-wheel strut load was 1.2 MN. Traffic was applied at 5 mph (8 km/h). This speed represents aircraft taxiing from the gate to the takeoff position. The South wheel track was loaded with a four-wheel dual-tandem type representing a Boeing 747 (B747) gear configuration. The dual wheel spacing was 44 in. (1,118 mm) and the tandem axle spacing was 58 in. (1,473 mm). Wheel loads of 45 kips (200.2 kN) per wheel similar in magnitude to the B777 loading case were applied to give a carriage load of 180 kips (800.8 kN). The load carriage containing both struts is a continuous system, therefore traffic speed for the B747 and B777 matched.

The CC1 tests indicated that applying a sequential offset load (wander) pattern to asphalt pavements could reduce or even negate rutting. It was observed that the downward residual deformation (rutting) caused by a pass of heavily loaded landing gear carriage is canceled by the upward residual deformation (heave) resulting from the pass of the same gear offset by wander (Hayhoe and Garg [1]). Figure 1 provides a simple diagram of the observed behavior and shows how the stress in a soil element offset from a load can change with a moving wheel.

The test data indicate that the sequential wander pattern reduces or even negates the expected shakedown effect possibly due to particle movement and rearrangement. The particle rearrangement in turn reduces the strength of the unbound layer causing future load applications to cause more residual deformation. The strength reduction can be due to a less dense particle matrix and/or grain abrasion, which would reduce the coefficient of friction between particle contact points and increase the potential for loads to cause inter-particle slippage. The investigation into unbound aggregate behavior found that aircraft load wander could cause the individual particles in unbound aggregate layers to slide, rotate, and shift positions in relation to one another (Donovan and Tutumluer [2, 3, 4]).

This paper describes the successful application of a stress history based approach developed at the Center of Excellence for Airport Technology (CEAT) research project at the University of Illinois for predicting final transverse rut profiles from transient residual deformation basins. The approach has the potential for estimating actual permanent deformation trends and accumulation rates of planned future pavement test section granular base/subbase layers by simply collecting residual deformation data from only a few hundred initial trafficking load cycles.

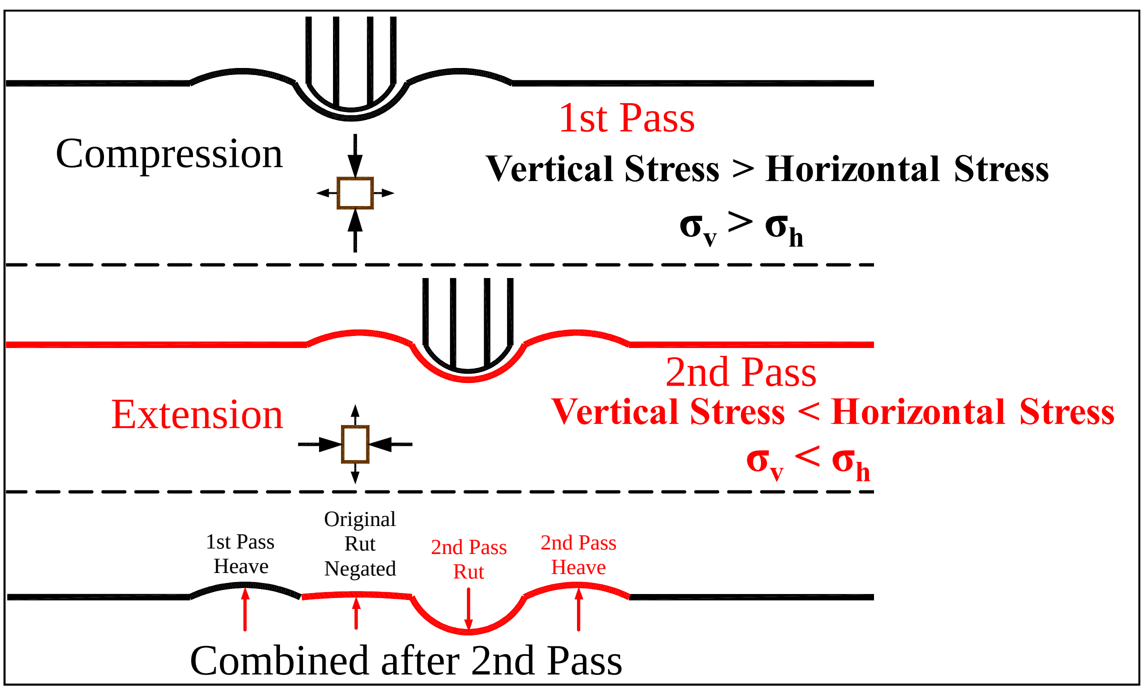

Figure 1. Schematic explaining the rut profile development from an offset wheel.

DEVELOPMENT OF RESIDUAL DEFORMATIONS IN NAPTF TEST SECTIONS BASED ON TRANSVERSE PROFILES

The surface transverse profiles of the NAPTF asphalt pavement test sections were recorded throughout testing by a transverse surface profiler (TSP) and a rolling inclinometer. Figure 2 shows typical transverse profiler data of the medium strength flexible conventional (MFC) test section over multiple passes. As can be seen, the MDDs were not positioned in the critical rut depth location. The actual location of the maximum rut depth coincided with the location of the maximum number of coverages from the gear carriages. A coverage was defined as the application of a wheel load on the critical pavement section. The maximum rut was recorded in more or less the center of the wander pattern where the maximum number of wheel applications and thus coverages occurred. The interesting item to note in Figure 2 is that the rut profile does not contain two distinct wheel depressions due to the applied dual wheeled traffic. It is the goal of this paper to explain how the residual deformation basin forms due to the applied traffic and provide a method to predict the formation of the basin using measured transverse profiles and including the effects of stress history.

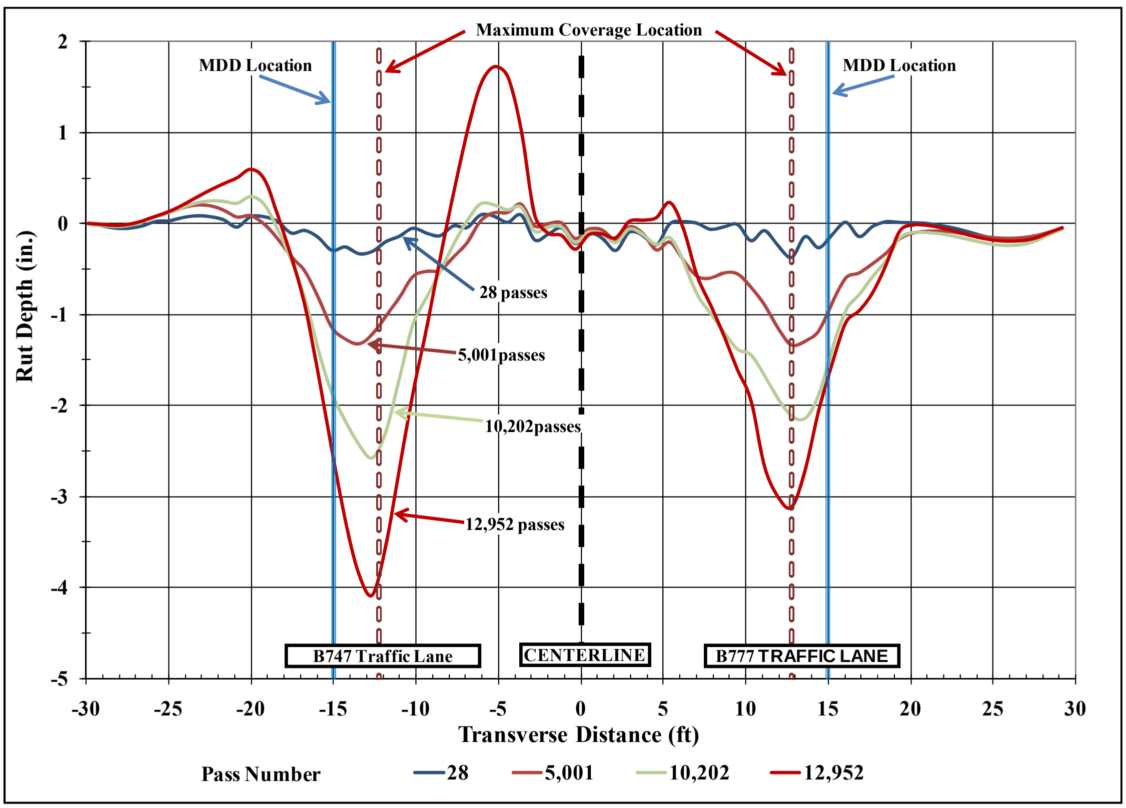

Figure 2. Surface transverse profile of MFC section throughout testing (1 in. = 2.54 cm).

CREATION OF THE TRANSVERSE SURFACE PROFILE USING MDD DATA

During the NAPTF testing, the transverse surface profile was not measured after each successive pass of the test vehicle. However, MDD data were recorded for each pass and the data could be used to “create” the transverse profile. The only way to use MDDs to measure the true transverse profile would be to have MDDs placed transversely across the pavement, which would be expensive and likely result in interference between sensor stacks. Because of the applied wander pattern, it was possible to use the MDD responses from the different wander positions to create a quasi-transverse profile due to a single gear carriage pass.

Figure 3a shows all wander positions and the associated MDD locations used in the CC1 tests. The stationary MDD readings measured during trafficking of the 9-wander positions, each providing a transverse profile data point and aligning the wheel paths as in Figure 3b, shows how the stationary MDD readings can be combined to create half of the transverse profile. If one assumes that the transverse profile is a mirror image, the MDD reading locations from Figure 3b can be inverted around the wander centerline and the complete transverse profile can be created, as shown in Figure 4. Due to different wheel spacing and different relative MDD locations, the “6-wheel” type dual–tridem gear lane and the “4-wheel” dual-tandem gear lane had slightly different locations for the MDDs in relation to the gear wheels and thus the MDDs provided slightly different transverse profile data points for each lane.

Using the approach outlined above, it is possible to develop transverse profiles for each travel direction and wander sequence for the NAPTF tests. However, as with all field measurements, there might be slight fluctuations in the MDD readings to create transverse profiles with peaks and valleys that do not occur in the actual transverse profiles and if these profiles were added, with the errors included, the resulting residual deformation basin would be influenced by these discrepancies and be incorrect.

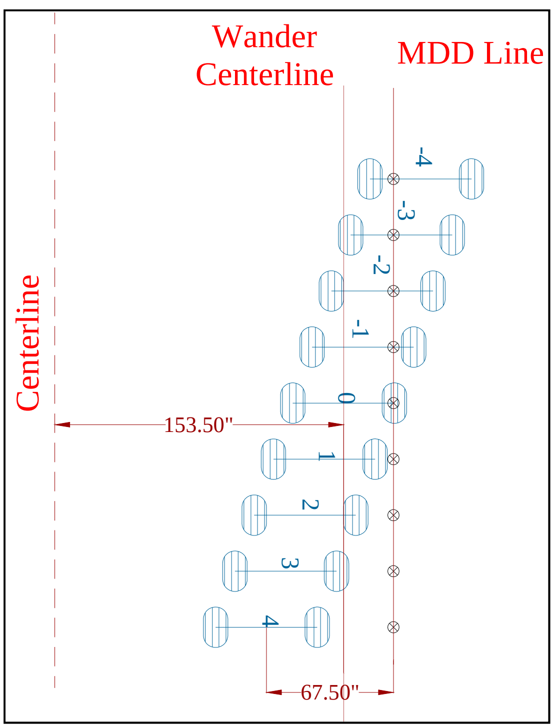

Figure 3a. NAPTF “6-wheel gear” wander pattern compared to the stationary MDD location.

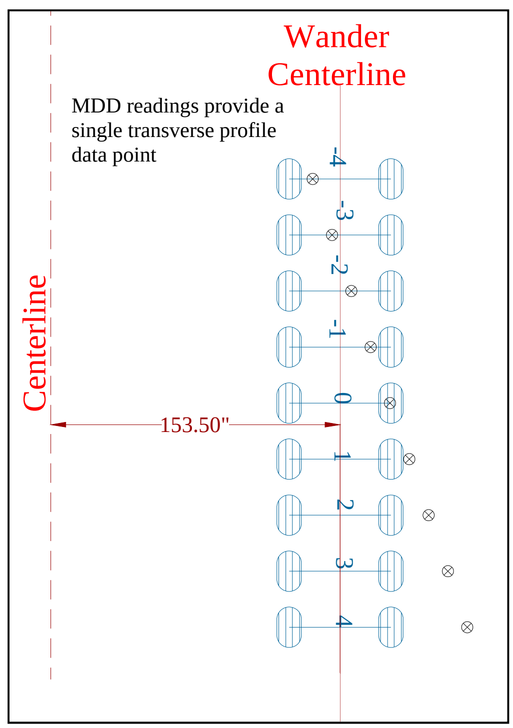

Figure 3b. MDD locations if the wheel paths are aligned

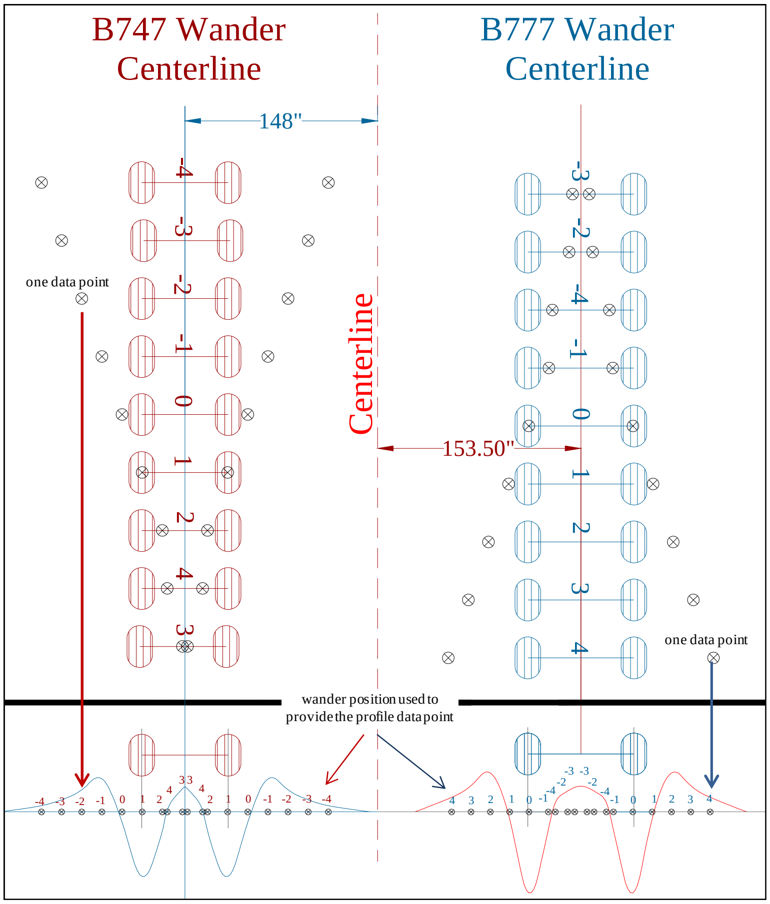

Figure 4. Using stationary MDD readings from an applied sequential wander pattern during NAPTF tests to create a surface transverse profile (1 in. = 2.54 cm).

The most prevalent errors occur between the gear wheels and are likely the result of readings that are provided from different wander positions at different passes in the wander pattern. In addition, the reading locations are close together between the gear wheels, and a 10-20 mil (0.25-0.5 mm) difference in the readings results in a dramatic change in the transverse profiles. To incorporate the fluctuations into the transverse profiles and then sum those transverse profiles would cause increasing errors in the cumulative deflection basin. Because of the fluctuations in readings and because there are only 18 measured data points for each transverse profile, a smoothing method is employed to calculate a complete transverse profile with calculated residual deformation values every 0.25 in. (6.35 mm).

The first step in the smoothing process is to determine which of the MDD readings are critical to creating the transverse profile. For the “6-wheel gear” lane, the two most critical points are wander position 0 and wander position 2 readings. These are consistently the minimum and maximum residual deformation values, respectively. Wander position 4 is used to provide a data point outside wander position 2 and the point of zero residual deformation is assumed to be 18 in. (457 mm) outside of wander position 4. Wander position 1 provides a data point between wander position 2 and 0 and is used as an inflection point. Wander position -1 is the next critical point and provides a point between the gear wheels. The maximum heave between the gear wheels is assumed to occur at the midpoint of the gear. These assumptions result in a transverse profile that is 171 in. (4,340 mm) wide for the "6-wheel gear" lane.

For the "4-wheel gear" lane, the critical points used are from wander positions -3, -1, 0, and 1; with 1 and -1 being the two most critical points. The transverse profile is again assumed to taper off 18 in. (457 mm) from the farthest critical point, wander position -3. This results in a transverse profile for the "6-wheel gear" lane that is 161.5 in. (4,100 mm) wide.

Once the "critical points" are known, the value of the residual deformation between these points is calculated. The calculation determines the transverse profile value between the two points by connecting them with a parabola that assumes one point is the vertex of the parabola and the other as a point on the parabola. Combining the parabolas results in a smooth transverse profile created using just the critical points. The value of the transverse profile is calculated every 0.25 in. (6.35 mm) and with the transverse profile values known every 0.25 in. (6.35 mm), it is possible to sum offset transverse profiles by aligning the readings.

Figure 5 shows one set of completed transverse profiles for a 66-pass wander pattern. There are 10 profiles shown in Figure 5 because for each 66 pass wander pattern there are 5 wander sequences which are traveled in both the West to East direction and the East to West direction. Note that there is a distinct difference between the residual deformation recorded during a West to East pass and the residual deformation from an East to West pass and there is a reduction in rut depth for wander sequence 5, as reported previously by Donovan and Tutumluer [2,3,4] but important to observe using this transverse profile creation method.

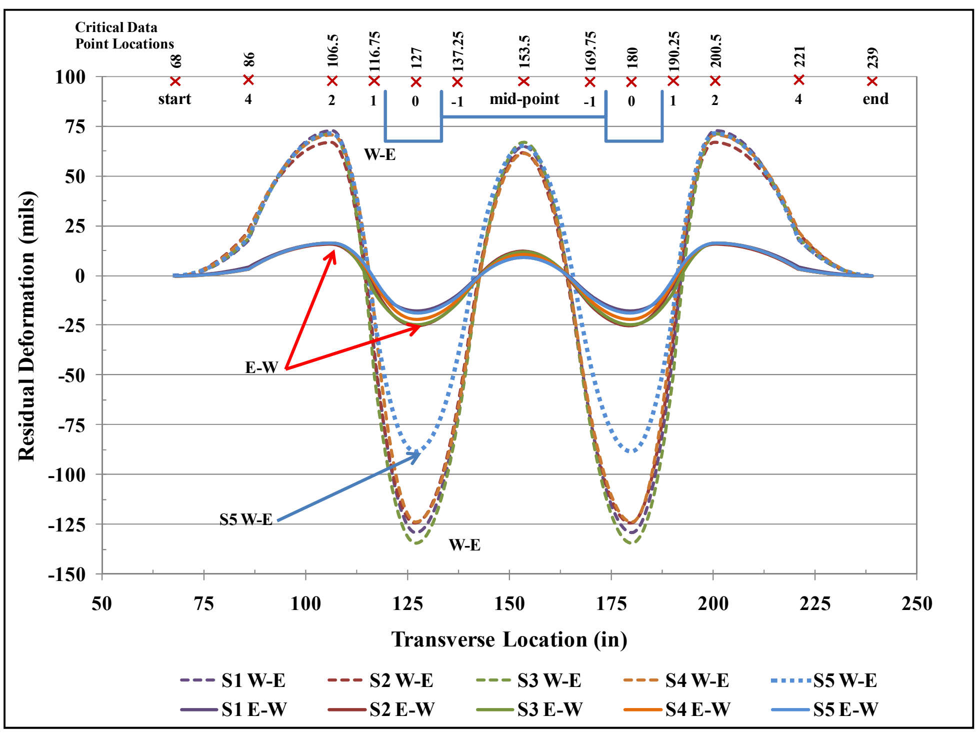

Figure 5. Example of calculated "6-wheel gear" transverse profiles created from MDD readings over a 66-pass wander pattern (1 in. = 2.54 cm).

DEVELOPMENT OF RESIDUAL DEFORMATION BASIN IN NAPTF CC1 TESTS

The residual deformation transverse profile from each wander sequence and travel direction can be combined to calculate the total residual deformation after a complete wander pattern. The residual deformation transverse profile does not show a distinct two-wheel path from the dual wheel axles because of the applied wander pattern and the rut and heave caused by each gear carriage pass (see Figure 2). The overlapping heave on an area that previously experienced a rut causes the rut depth to decrease, which was one of the main observations that led to this research.

The residual deformation (heave and rut) increases with the number of passes as clearly visible in Figure 6 for the MFC Section “6-wheel gear” lane, in the West to East direction. The rut and heave amounts increase as the number of passes increases and there is a marked increase in both at around 5,000 passes when the asphalt temperature increased.

The summation of the individual calculated transverse profiles from each pass of a 66-pass wander pattern results in a bowl shaped depression that matches the contour of the measured transverse profile. If just the rut amount is used to calculate the deformation basin, a similar bowl shape appears, but the rut depth is greater and there is no heave outside the traffic lane as it occurs when the heave is included in the calculation. Figure 7 shows the residual deflection basin calculated using just the maximum rut caused by wander position 0 in the “6-wheel gear” lane and the basin found using both the rut and the heave values. In this example, the rut depth without including the heave in the transverse profile is 60% greater than the rut depth found using the heave value. Only by using the true transverse profiles that include both rutting and heaving can the summation of transverse profiles over 66 passes result in a recovery of some of the downward residual deformation.

Figure 8 compares the calculated and measured transverse profiles of the MFC section, “6-wheel gear” lane. The calculated profile shown in Figure 8 is for one 66-pass wander pattern as that starts at 5,000 passes. The peaks and somewhat jagged nature of the created transverse profile are due to the discontinuous measurements taken to form the profile. The created profile is fashioned from only five actual measurements with assumed starting and ending points added to the profile; this is then inverted to create the total profile. In other words, the actual continuous profile from a single pass is not known and the assumed inflection points and shape of the created transverse profile may not exactly match reality. However, the shape of the created transverse profile is logical and does provide a reasonable residual deformation basin.

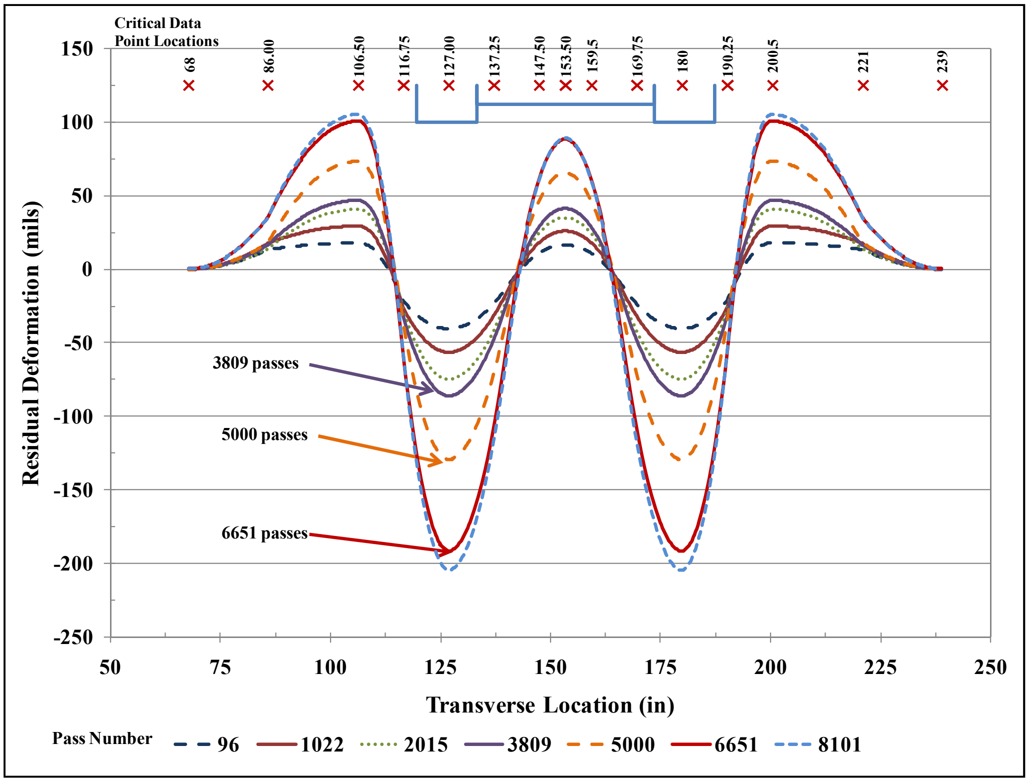

Figure 6. Transverse profiles from different traffic levels in MFC section, "6-wheel gear" lane, W-E direction.

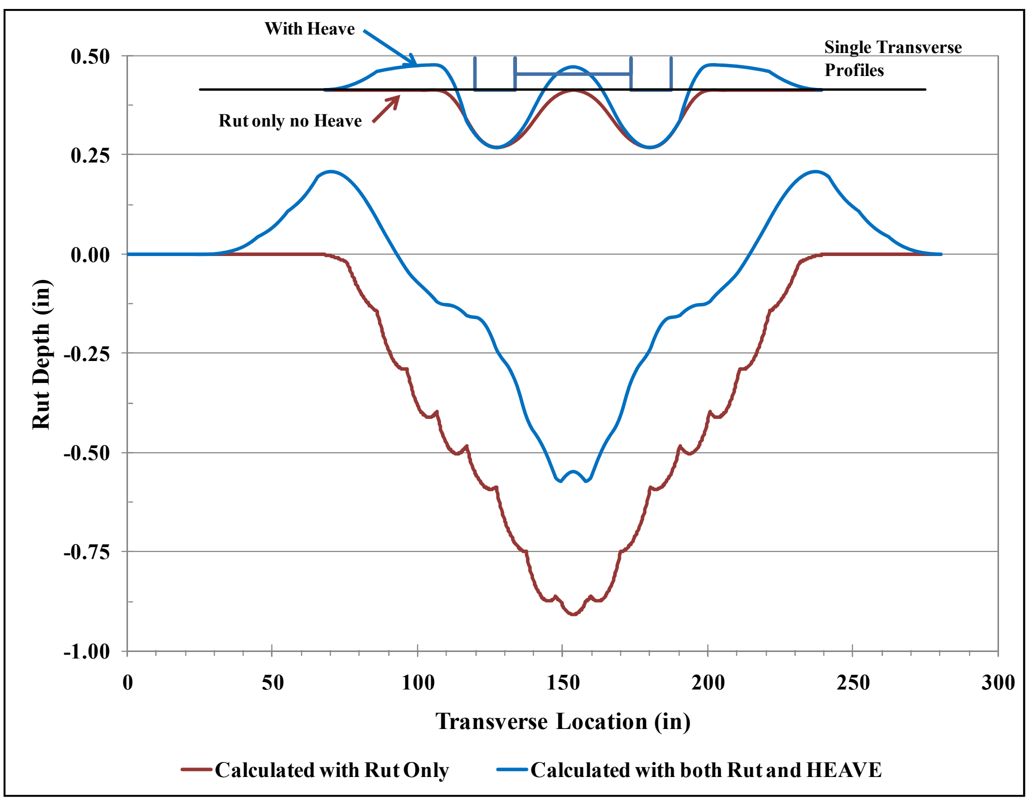

Figure 7. 66-pass residual deformation basins from rut only and rut plus heave calculations.

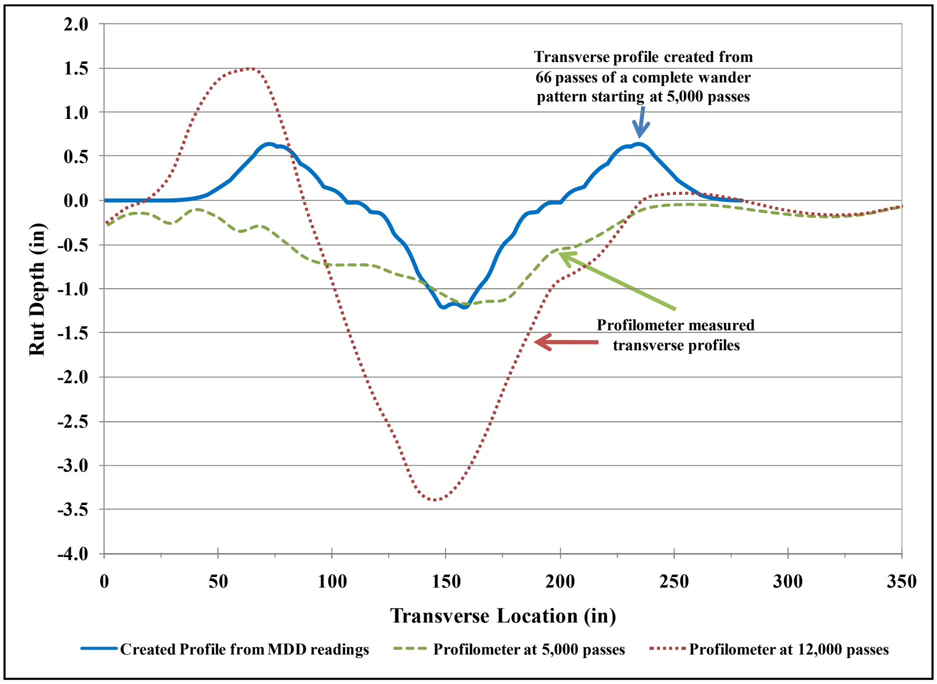

Figure 8. Created transverse profile from MDD readings and profilometer measured transverse profiles from MFC section, "6-wheel gear" lane (1 in. = 2.54 cm).

Figure 9 shows that, as expected, the depth of the rut and the amount of heave of the MFC section, "6-wheel gear" lane transverse profiles created with the MDD readings increase with an increasing number of passes. However, if the transverse profiles readings are simply added (which is required to determine the future shape of the transverse profile due to continued trafficking), the magnitude is much greater than the actual profilometer measured transverse profile shown in Figure 10. That is, if the created transverse profiles are summed over the actual number of complete 66-pass wander patterns covered in 5,000 passes, the rut depth and heave amount are much greater than the measured values. In fact, even if the transverse profile created with the minimum MDD readings from the first complete wander pattern is used as the standard profile over 66 passes, the resulting accumulated rut and heave are 30-80 times the measured amounts. The same trend is observed in the accumulated transverse profiles in the MFC "4-wheel gear", MFS, LFC, and LFS sections. The shapes of the created transverse profiles closely follow the profilometer measured profiles, but if the created transverse profiles are summed for the number of complete 66-pass wander patterns, the magnitudes of the created profiles exceed those in the field.

There could be many causes of this disparity between the created and measured transverse profile; but the two most obvious ones are as follows: (1) small variations in the MDD readings used to form the created transverse profiles are multiplied over thousands of passes creates significant fluctuations and errors and (2) when creating a transverse profile from MDD readings, the amount of rut or heave measured may not be the actual transverse profile rut or heave because the measured value is dependent on the last pass. The amount of rut or heave in an unbound aggregate layer is greatly dependent on whether the soil element experienced rut or heave in the last pass; if the element was compressed in the previous pass, it will heave more in the next offset pass, etc. Likewise, if the element heaved in the last pass, it will rut more in the next pass when the load is directly over the element. The importance of stress history effects on the behavior NAPTF P209 and P154 granular base and subbase layers has been well documented by Kim and Tutumluer [5]. By including stress history adjustment factors into the rutting prediction equations, they could more accurately predict actual permanent deformations in laboratory and full scale tests. Therefore, stress history effects must be considered when creating the transverse profiles or the prediction of the future transverse profile will be inaccurate.

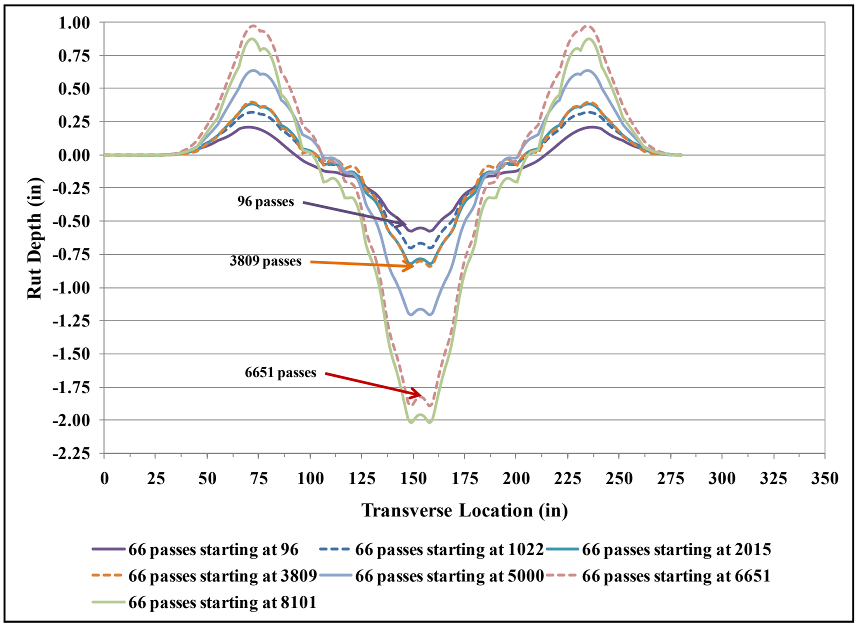

Figure 9. Created transverse profiles from MFC section, “6-wheel gear” lane for various passes.

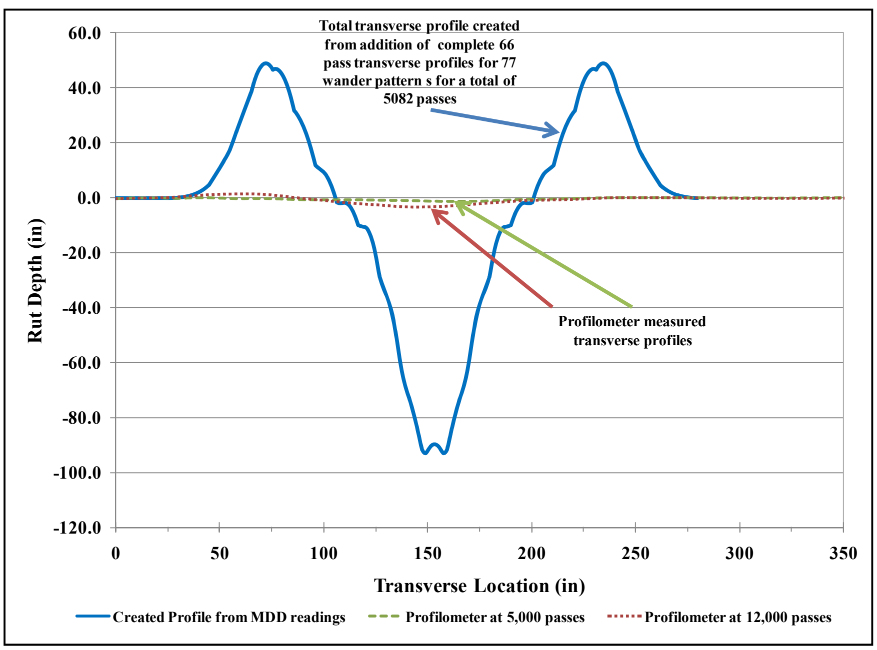

Figure 10. Created transverse profile from 77 complete wander patterns (5082 passes) and measured transverse profiles from MFC section, “6-wheel gear” lane (1 in. = 2.54 cm).

Regardless of the cause or the magnitude of the disparity between the created transverse profiles from MDD readings and the measured profiles, the only way to account for the rut reduction and continuous rutting and heaving (or "weaving") of the pavement surface due to the sequentially applied wander pattern is to consider an area of heave in the transverse profile calculation. The next section will discusses a method to use together the measured MDD readings, the profilometer measured transverse profiles, and stress history effects in order to create a single pass transverse profile and predict rut accumulation in the NAPTF test sections.

TRANSVERSE RUT ACCUMULATION DUE TO AIRCRAFT WANDER

It is not difficult to predict the final shape of a residual deformation basin using a measured transverse profile because all that is required is the location of the gear wheels for each wander position and the number of times those wander positions are trafficked. However, as was explained in the previous section, it is extremely difficult to predict the magnitude. This section provides a reasonable method of using the residual transverse profile caused by an individual aircraft pass and the measured transverse profile after a complete wander pattern to predict the final transverse profile from multiple passes.

In creating the residual transverse profiles using the MDD data, unique relationships were found to exist between the maximum downward residual deformation caused by the first pass in a wander pattern and the critical transverse points. If the maximum downward residual deformations from wander position 0 for the "6-wheel gear" measured lane and 1 for the "4-wheel gear" lane are taken as the standard, then comparing the other critical point residual deformations reveals relatively consistent ratios for each subgrade; Table 1 lists the ratios.

Table 1: Ratios of residual critical point values and the maximum critical point value used for calculating transverse surface profile

	MFC "6-wheel gear" NE MDD	
	W-E Avg	**E-W Avg**
4 MULTIPLER	-0.17	-0.05
2 MULTIPLIER	-0.51	-0.15
0 MULTIPLIER	1.00	0.22
Midpoint Multiplier	-0.46	-0.09

	MFC "4-wheel gear" **SE MDD**	
	W-E Avg	**E-W Avg**
-3 multiplier	-0.15	-0.03
-1 multiplier	-0.54	-0.16
1 MULTIPLIER	1.00	0.20
Midpoint Multiplier	-0.30	-0.04

Table 1 indicates that the maximum heave (2 multiplier for the "6-wheel gear" lane and -1 multiplier for the "4-wheel gear" lane) is approximately 50% of the maximum rut caused by the first pass in the West to East direction (0 multiplier for the "6-wheel gear" lane and 1 multiplier for the "4-wheel gear" lane) regardless of the section. On the return pass in the E to W direction, the rut is dependent on the section but for the MFC section was 20-22% of the maximum rut from the first pass. The heave on the return pass is approximately 15-16% of the maximum rut.

Using the information provided in Table 1 it is possible to create a transverse profile that will produce the same rut depths and surface transverse profiles measured by the profilometers in the CC1 tests. This new model uses the residual transverse profile after application of a complete wander pattern to determine the individual pass and complete test transverse profiles. Figure 11a shows the MFC section “6-wheel gear” lane with the calculated and measured transverse profiles. Figure 11b shows the same for the “4-wheel gear” lane. What is readily apparent is that the calculation of the residual deformation comes close to matching the maximum value, but the transverse profiles are somewhat off. It seems as if the real world has a wider deformation basin with less heave than the calculated values. The most obvious explanation for this disparity is that the residual transverse profile from each pass is affected by the residual profile of the previous pass. Essentially, if the stress history effects are ignored, it is difficult to predict the transverse surface profile seen in the full-scale NAPTF tests. This conclusion supports the findings of other researchers who emphasized the necessity of considering stress history effects when determining the rut caused by full-scale traffic with wander (Kim and Tutumluer [5], Kim [6]).

If the calculation of the transverse profile is corrected by considering the residual deformation of the previous pass, it is possible to come up with a closer solution. To correct the calculation, a comparison of the expected single pass transverse profile and the transverse profile caused by the previous pass is made. That is, if the previous pass caused a rut and the current pass is supposed to cause a rut in the same position, then the additional rut is less. Likewise, if the previous pass caused a heave and the new pass causes a heave, the heave will be less. Based on the results of discrete element modeling in Donovan et.al. [7] and Donovan and Tutumluer [8] and the reduction in rut and heave observed when changing directions on the same wander position, this seems like a logical and reasonable way to correct for the previous pass.

To account for stress history effects it is assumed that if the previous pass caused the same type of residual deformation as the current pass, then the residual deformation by the current pass is reduced by multiplying the current pass residual deformation value by a constant reduction factor based on the return pass multipliers from Table 1. A more accurate method of calculation would have a graduated influence factor based on the magnitude of the difference between the previous and current pass residual deformation values; however, that influence factor can only be computed with additional testing. Regardless, this first attempt at using the influence of the previous pass on the current one is indeed promising. The advantage to using the stress history correction procedure is that any combination of wander positions can be simulated to predict the future deformation basin.

Figure 12 shows the calculated surface transverse profile for the MFC “6-wheel gear” lane again, but this time the calculation corrects for the previous pass. By considering the stress history effects, the magnitude of the calculated residual deformation and the width of the deflection basin coincide more closely with the measured values. The sharp peaks are a result of the rough estimation of the effects of the previous pass. Although it is possible to reduce the jagged nature of the calculated transverse profiles by graphing a 50-point moving average of the calculated values, the presented graph indicates improvements to the method are still needed.

SUMMARY AND CONCLUSIONS

This paper examined the pavement transverse profiles to predict rut development during the FAA’s NAPTF pavement tests. The use of the collected stationary MDD data to develop the transverse profile across the pavement was discussed first. Essentially, the applied sequential wander pattern provided the offset data points to create a complete transverse profile 171 in. (4,300 mm) and 161.5 in. (4,100 mm) wide for the "6- and 4-wheel gear" lanes, respectively.

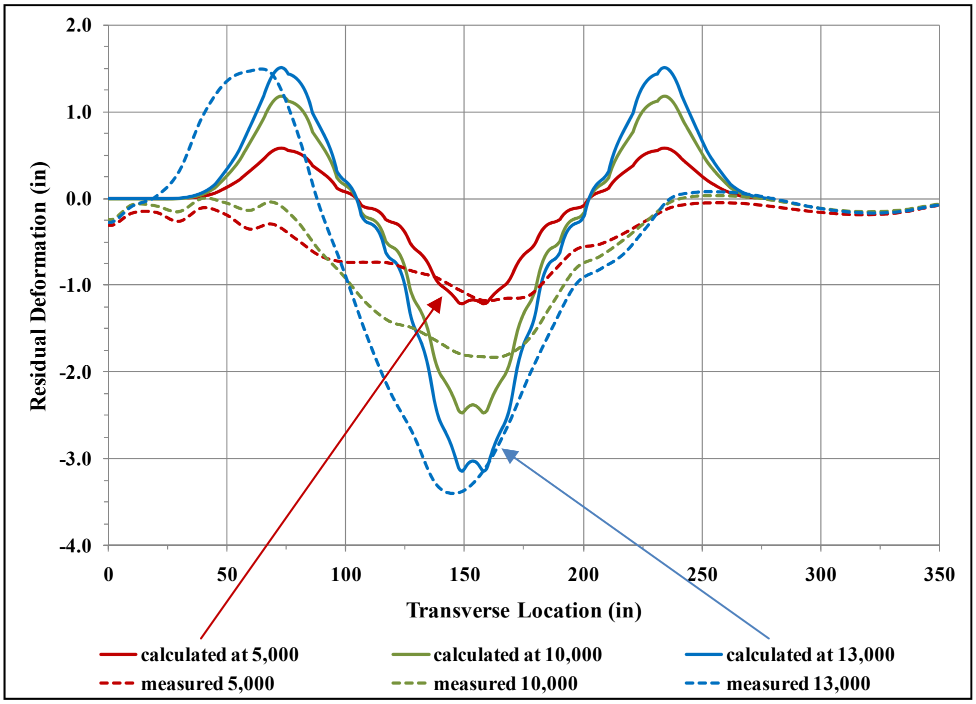

Figure 11a: Comparison of calculated and measured profiles in the MFC, "6-wheel gear" lane

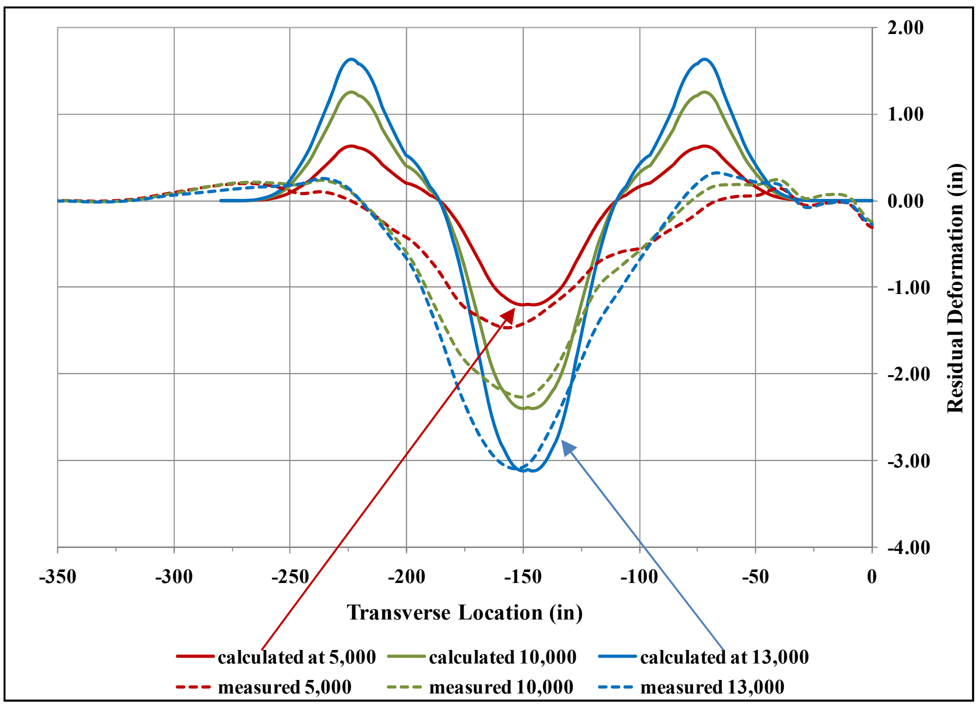

Figure 11b: Comparison of calculated and measured profiles in the MFC, "4-wheel gear" lane

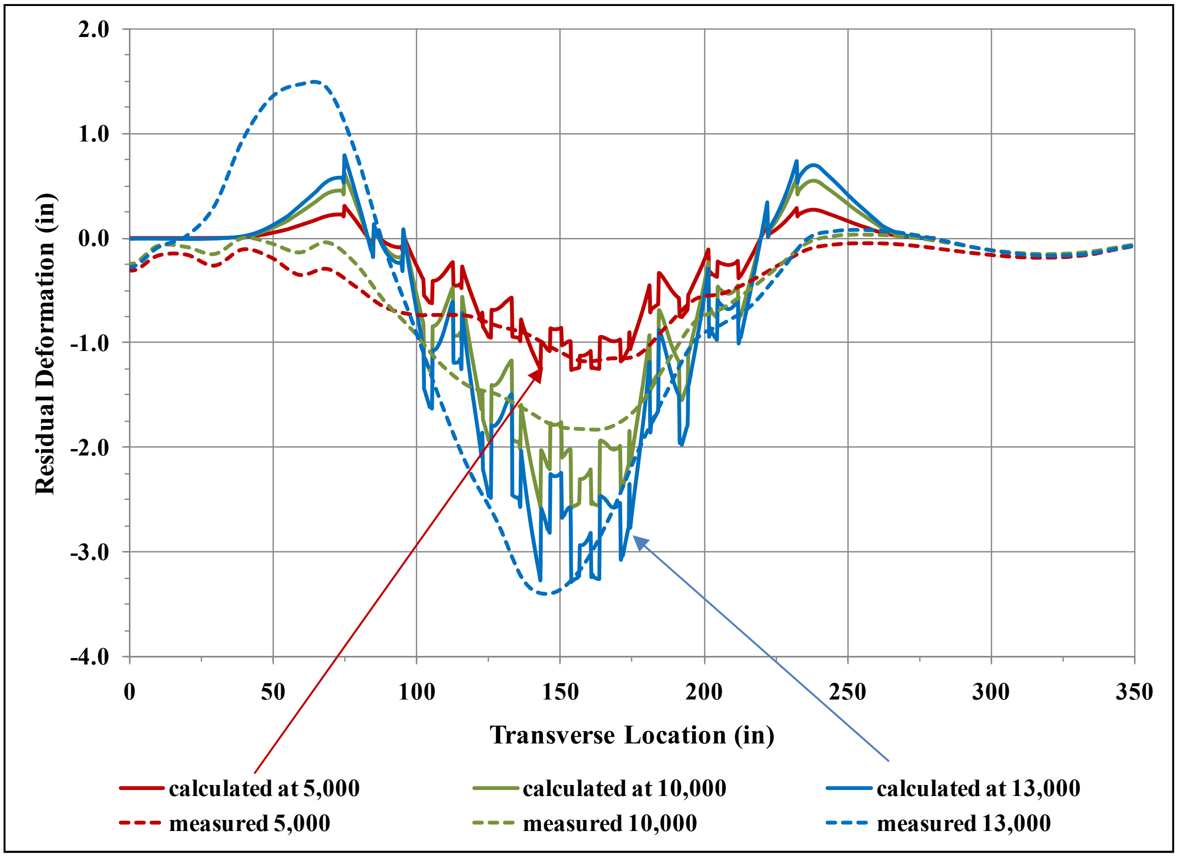

Figure 12: Comparisons of corrected calculations for stress history effects and the measured profiles in MFC section, "6-wheel gear" lane

The residual deformation basins were established during the Construction Cycle 1 (CC1) tests at NAPTF. Using the MDD values to create the transverse profiles produced a reasonable residual deformation basin, but the magnitude of the rut and heave when compounded over multiple 66-pass wander patterns greatly exceeded the measured amounts. This discrepancy was likely caused by MDD reading variations and previous stress history (rut or heave) effects.

A method of critical points was proposed to develop a transverse profile for each pass and calculate the transverse profile created by multiple passes in the "4- and 6-wheel" gear lanes. This method was based on the relationship between the maximum residual MDD readings due to various wander positions. It was found that the ratio of the critical MDD readings to the maximum downward residual deformation was relatively consistent. The maximum heave caused by each pass was approximately 50% of the maximum rut recorded by each pass. Using the measured transverse profile from a single 66-pass wander pattern it was possible to create a theoretical individual pass transverse profile that when combined over the 66-pass wander pattern produced a residual deformation basin similar to the measured profile.

The initial attempt at using this method did not consider previous load applications when determining the rut or heave of the current pass and thus both the rut and heave were larger than the measured values. By considering the previous pass and thus stress history, it was later possible to produce a more accurate residual deformation profile that eliminated the excessive heave seen in the original calculations.

ACKNOWLEDGEMENTS

This paper was prepared from a study conducted in the Center of Excellence for Airport Technology (CEAT). Funding for CEAT is provided in part by the Federal Aviation Administration (FAA). The CEAT is maintained at the University of Illinois at Urbana-Champaign. Ms. Patricia Watts is the FAA Program Manager for Air Transportation Centers of Excellence and Dr. Satish Agrawal is the FAA Airport Technology Branch Manager. The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the FAA. This paper does not constitute a standard, specification, or regulation.

REFERENCES

1. Hayhoe, G.F. and Garg, N. "Subgrade Strains Measured in Full-scale Traffic Tests with Four and Six-wheel Landing Gears," Proceedings of the FAA Airport Technology Transfer Conference, Atlantic City, NJ, USA, May 5-8, 2002.

2. Donovan, P.R. *Analysis of Unbound Aggregate Layer Deformation Behavior from Full Scale Aircraft Gear Loading with Wander,* Ph.D. Dissertation, University of Illinois at Urbana/Champaign, Urbana, IL, July 2009.

3. Donovan, P.R. and Tutumluer, E. "The Anti-Shakedown Effect," Proceedings of the 1st International Conference on Transportation Geotechnics, Nottingham, England, August 2008.

4. Donovan, P. and Tutumluer, E. "Effect of Aircraft Load Wander on Unbound Aggregate Pavement Layer Stiffness and Deformation Behavior," Proceedings of the Transportation and Development Institute of the American Society of Civil Engineers Airfield and Highway Pavements Specialty Conference, Bellevue, WA, October 2008.

5. Kim, I.T. and Tutumluer, E. "Rutting Evaluation of Airport Pavement Granular Layers Considering Stress History Effects," Proceedings of the Airfield and Highway Pavement Specialty Conference, 2006, pp. 566-577.

6. Kim, I.T. *Permanent Deformation Behavior of Airport Flexible Pavement Base and Subbase Courses*, PhD Dissertation, University of Illinois, 2005.

7. Donovan, P.R., Tutumluer, E., and Huang, H. "Use of 3-dimensional Discrete Element Model to Examine Aggregate Layer Particle Movement due to Load Wander," Proceedings of the 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields (BCR^{2}A'09), The University of Illinois at Urbana-Champaign, Champaign, Illinois, June 29-July 2, 2009.

8. Donovan, P.R. and Tutumluer, E. "Investigating Unbound Aggregate Deformation Behavior Due to Traffic Wander Using Discrete Element Modeling." In Preprint CD-ROM of the 89th Annual Transportation Research Board Meeting, Washington D.C., 2010.