ANALYSIS OF PAVEMENT RESPONSES TO AIRCRAFT AND ENVIRONMENTAL LOADING AT DENVER INTERNATIONAL AIRPORT

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ABSTRACT

Monitoring in-service pavements is important for further understanding the pavement behavior under repeated loading. Many road tests were constructed for understanding the behavior of concrete pavements under highway truck loading. However, there has been very limited testing and monitoring of airport pavements. At the Denver International Airport, dynamic and static sensors were installed in the pavement structure during construction of runway 34R-16L in 1994. These sensors are used to monitor pavement responses due to aircraft loading and environment. This paper focuses on the analysis of displacements produced by two critical aircraft types: B-777 and B-727. A sensitivity analysis of the calculated displacement profiles was conducted for several input parameters using the ILLI-SLAB finite element program. Data acquired from thermocouples, position sensors, and deflectometers placed in the runway pavement are compared to the analytical results. Data from position sensors are used to determine the transverse gear load position for each aircraft within the instrumented section. Thermocouple readings were used to determine the temperature profile to be used in the numerical analysis to calculate responses for combined aircraft and environmental loading.

INTRODUCTION

The contributions of Westergaard (e.g., 1926, 1939, and 1948) to analyze concrete pavement responses due to traffic load have been extremely valuable. It was the most used model to analyze concrete pavements when computers were not available. Among the limitations of his model are: inability to analyze multiple slabs, base layers, finite-sized slabs, and base-slab separation. Although efforts have been made to overcome some of these limitations using dimensional analysis (e.g., Ioannides, 1990, and Salsilli, 1991), there is no correction factor to be applied to Westergaard's equations to calculate stresses and displacements other than at the interior, corner or edge. However, programs based on Finite Element Method (FEM) allow for such analysis. The main objective of this paper is to match slab deflection profiles measured from the field as aircraft travel along the runway, with an existing finite element program. The ILLI-SLAB, program developed originally by Tabatabaie and Barenberg (1978), is currently being used to calculate deflections for comparison to the deflection readings obtained from the Denver International Airport (DIA). The ILLI-SLAB program was chosen initially because it is a fast and proven way to perform complex rigid pavement analysis and allows for quick determination of the most sensitive variables affecting pavement response.

Two aircraft types were used in this study: B-727 and B-777. They represent two very different gear configurations present on airfields: single and tridem gears. The following are the key parameters required to compare predicted responses with measured deflection readings: joint

Load Transfer Efficiency (LTE), modulus of subgrade reaction (k-value), aircraft lateral position, gear type, load level, temperature distribution through the slab depth, and concrete coefficient of thermal expansion. Other important variables not included due to lack of information were initial slab warping, depth of bedrock, and exact interface condition between concrete slab and base (bonded, unbonded or partial friction).

PROJECT BACKGROUND

The project entitled "Analysis of Data from Denver International Airport" is an ongoing project between the University of Illinois at Urbana-Champaign (UIUC) and the Federal Aviation Administration (FAA) through the FAA Center of Excellence for Airport Technology (COE). "Runway Instrumentation at DIA" is part of a FAA major research effort initiated in 1992 to study concrete pavement responses and performance using field data (Dong *et al.*, 1997). The FAA COE project has focused on pavement responses due to different loading conditions (aircraft) and environment (temperature and moisture). The overall objectives of this project are to analyze pavement responses due to aircraft loading, evaluate the rate of changes in responses over time, investigate effects of short- and long-term variations in temperature, and slab moisture content, evaluate load transfer mechanisms and effects of environmental changes on load transfer over time, and study the effects of combined traffic and environmental loads on airport pavement responses.

Sixteen slabs were instrumented in the take-off area of runway 34R at DIA. The instrumented section is located 121.9 m (400 ft) from the runway threshold and is 22.86-m (75-ft) wide and 24.38 m (80-ft) long. There are about 460 static and dynamic sensors to monitor different pavement responses (Dong *et al.*, 1997). Dynamic sensors are triggered only when an aircraft passes, collecting strains, vertical displacements, and aircraft information (position, speed, and acceleration). Every aircraft pass is stored in the database as an event. Infrared sensors identify the aircraft speed and acceleration, and trigger the dynamic sensor data collection. Position sensors are used to identify the aircraft location. The static sensors collect data related to environmental changes in the concrete slab due to temperature and moisture, such as joint movement and strain within the pavement structure. The instrumentation in the pavement structures was placed by the U.S. Army Corps of Engineers, Waterways Experiment Station (Lee e*t al.*, 1997). Figure 1 shows the location of the deflection sensors (LVDT's), thermocouples, and position sensors used at DIA. There are two types of LVDT's: single- and multi-depth deflectometers (SDD and MDD). SDD's measure deflections at the mid-depth of the concrete slab, whereas MDD's also measure deflections at various depths in the base and subgrade. Figure 2 shows the pavement structure. The concrete slabs are nominally 43.2-cm (17-in) thick, 6.10-m (20-ft) long, and 5.72 m (18.75-ft) wide. There are three types of joints in the instrumented section: doweled, dummy, and hinged joints, as shown in Figure 3.

The instrumentation data are processed and stored in an ORACLE7 database, which can be accessed through the World Wide Web at http://www.airtech.tc.faa.gov/DENVER/. The database is managed by the Airport Technology R&D Branch, AAR-410, at the FAA William J. Hughes Technical Center. The database is comprised of a series of tables organized into five main groups: dynamic sensors, static sensors, dynamic and static sensors, miscellaneous, and HWD tests.

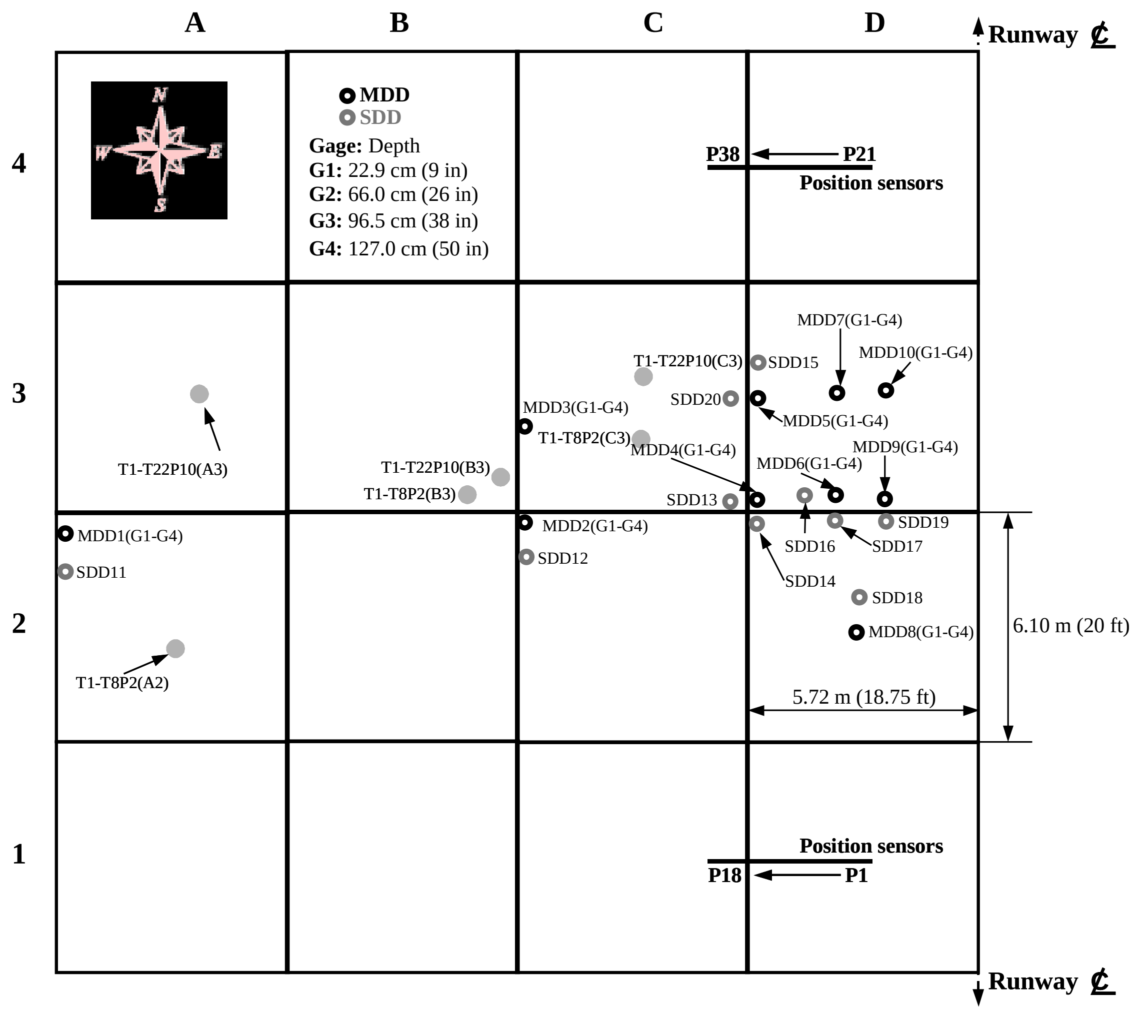

Figure 1. Pavement instrumentation

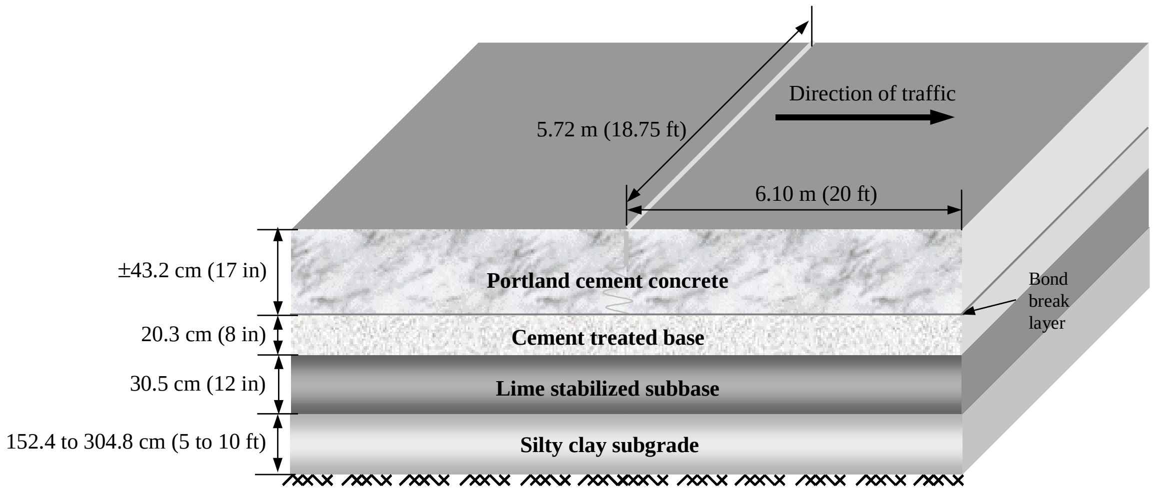

Figure 2. Pavement structure at DIA

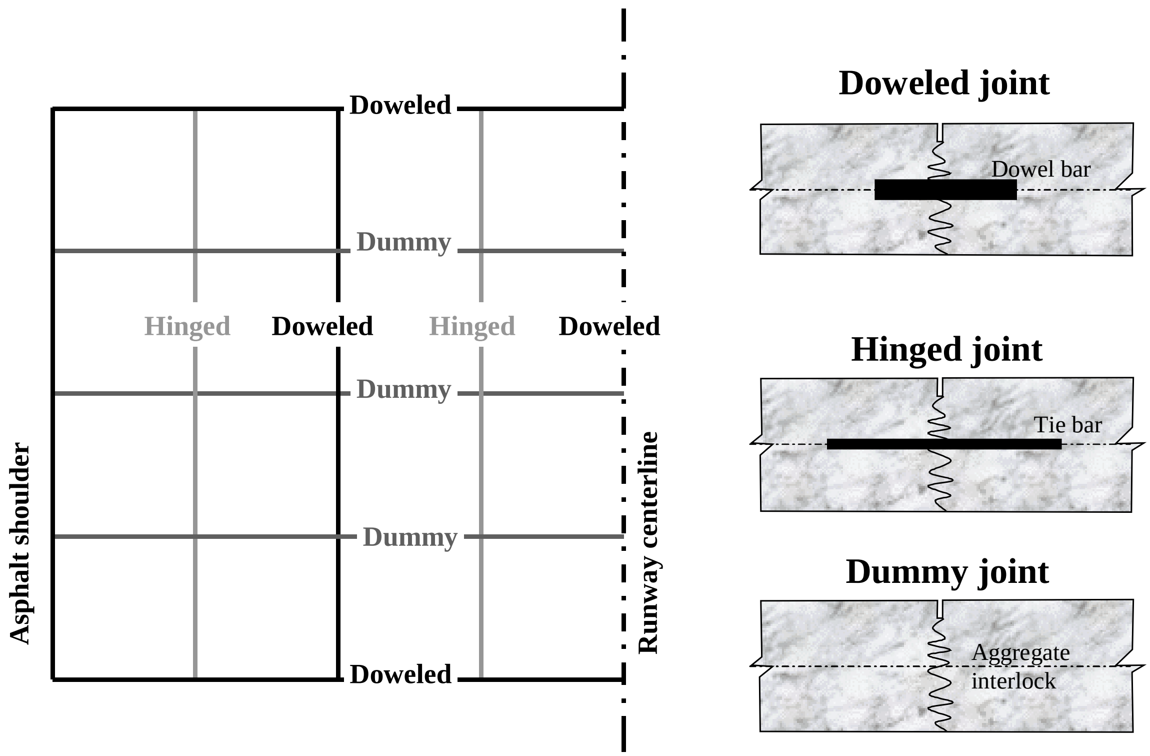

Figure 3. DIA joint design

The user can either perform an automatic or a manual query. In the former, the user can download a package of information, whereas in the latter, the user can specify the query using Structure Query Language (SQL). Lee *et al.* (1997) gave additional information about the organization of the database on the World Wide Web. Dong and Hayhoe (1999) described in detail the data processing and the design of the original database structure. Some additional information about processing of the raw data from the dynamic sensors for storage in the database was also given by Dong e*t al.* (1997).

ANALYSIS PARAMETERS

Dense liquid and elastic solid are the two main soil models for characterizing a concrete pavement foundation. These are in fact two extreme models and the soil does not completely behave as a pure dense liquid or an elastic solid. Some agencies like the Portland Cement Association (Packard, 1984) and AASHTO (1993) recommended an increase of the subgrade k-value due to the existence of a base. Ioannides *et al.* (1992) and Darter *et al.* (1994) recommended that the structural contribution of the base layers must be combined with the concrete slab instead of the subgrade.

Preliminary backcalculation results for DIA based on Heavy Weight Deflectometer (HWD) data have shown that backcalculated k varies only 2% when the cement treated base (CTB) is included in the analysis, assuming an unbonded condition. However, if the condition is bonded, the backcalculated k-value is reduced by 37% compared to the backcalculated k-value using an unbonded base layer. Since a bond breaker between the slab and base (Harrison, 1997) was utilized at DIA, an unbonded condition was assumed in the analysis. As a result, the base layer could be ignored due to its limited contribution to the slab responses.

A uniform k-value was used in this analysis, recognizing that k-value is not always the same and can be different at the slab corner and edge versus the slab interior (Ioannides *et al.*, 1985). The baseline k-value used in the present analysis is equal to the design subgrade k-value multiplied by a factor of two to take into account the increase in magnitude of k due to the effect of dynamic loading (Darter *et al.*, 1994, and AASHTO, 1993). DIA pavement design was based on a k-value of 40.7 MPa/m or 150 psi/in (Isbill Associates, 1991) and therefore, a dynamic k-value of 81.4 MPa/m (300 psi/in) will be used as standard value throughout the sensitivity analysis. Brill (2000) performed a 3-D Finite Element Analysis (FEA) using a modulus of elasticity of 103.4 MPa (15,000 psi) for this soil, based on laboratory resilient modulus test results.

The first challenge was to identify the path of the aircraft within the instrumented section. The interpretation of the position sensor readings allowed for automated determination of the gear path. Rufino *et al.* (2001) explain the methodology behind this approach. However, not all aircraft passes (events) could be identified due to insufficient information from the position sensors. Events, which could not be located laterally on the pavement, were not included in the analysis. For the events analyzed, the gear path was located within a ±0.31 m (±1 ft) interval. The weight of the aircraft also needs to be known to reproduce the measured deflections. According to Dong *et al.* (1997), the aircraft weight is obtained from the departing aircraft list at the airport. Although there were 172 B-777 events in the database, only 10 events were initially considered for analysis because either the gear path could not be identified or the aircraft weight was not available. There were 2937 Boeing 727 events listed in the database, including the series 100 and 200 aircraft, but only 525 could be considered for analysis for the same reasons as given above.

Static sensors were set-up to collect data on an hourly basis. However, data were not available for all times of the year due to sensor or data acquisition malfunctions. Several authors, e.g. Faraggi *et. al* (1987), Barber (1957) and Dempsey *et al.*(1984), proposed analytical or numerical approaches to predict pavement temperature with depth given standard climatic data. However, for this paper, only events that have pavement temperature data within 30 minutes from the time the aircraft passed have been considered for the analysis. The year, day and time of the dynamic sensor reading for each aircraft pass has been checked against the thermocouple data available from in-situ measurements. For instance, there are 10 B-777 and 525 B-727 events that have both weight and gear path available, but there are no pavement temperature data for 3 B-777's and 156 B-727's. Therefore, 7 B-777's and 369 B-727's events have been used for pavement response analysis.

LTE across the joints significantly affects concrete pavement responses at the edge. For instance, if the load is applied at a transverse joint that has a LTE of 100 percent (aggregate interlock only), the pavement responds closer to an interior loading condition rather than edge. On the other hand, if the LTE approaches 0 percent, the pavement loading is closer to free edge than interior loading. For airports, LTE it is usually obtained using through analysis of HWD data. However, the LTE obtained with HWD is not necessarily the same as the in-service value based on deflection and strain measurements (Brill, 2000). Brill (2000) describes two methods to calculate in-service LTE based on deflections and strains. One is based on deflection or strain measurements on opposite sides of a joint, while the other is based on the shape of the deflection or strain profile of a single sensor at the transverse joint. Based on the deflection method, Brill (2000) obtained a good correlation (coefficient of correlation, r, of 0.851) between LTE for a B-727 gear load and concrete surface temperature at a dummy joint. Kapiri *et al.* (2000) also correlated average pavement temperature with LTE for dummy joints based on HWD tests for the DIA project. By means of an Analysis of Variance (ANOVA), Brill (2000) concluded that the difference mean LTE based on deflection for different aircraft types is significant during winter, but not during the summer.

FEA has shown that LTE depends on the geometry of applied load, location of the applied load near the joint, as well as elastic properties of the pavement system (Hammons and Ioannides, 1997). LTE based on different responses (deflection, stress or strain) will also give different results. Ioannides and Hammons (1996) show that the relationship between LTE based on deflection or stress is highly dependent on the ratio between radius of the applied load and radius of relative stiffness. Ioannides and Hammons (1996) corroborated Ioannides and Korovesis (1990a) statement that LTE based on deflection ratio is insensitive to the ratio of the radius of applied load and the radius of relative stiffness.

STRUCTURAL ANALYSIS

The structural analysis performed in this study aims to predict deflections measured from the dynamic MDD's placed within the instrumented section. The complete time-history of the LVDT readings for a particular event was used for comparison with ILLI-SLAB. For several gear positions across the slab, the deflections at the various sensor locations (influence lines) were calculated using the ILLI-SLAB program. For each aircraft event analyzed, the load was placed at 305 mm intervals in the direction of traffic. Only four slabs were used in this analysis due to the large number of runs that had to be performed.

The ratio c/h (element width or length over slab thickness) of the ILLI-SLAB mesh used varied between 0.30 and 0.53. Ioannides (1984) recommends that this ratio should be at most 0.8 and 1.5 to give accurate stress and deflection results, respectively. Nodes were included at the position of the LVDT sensors. Two different aircraft events were selected to perform a sensitivity analysis of deflection profiles. The selected events occurred about the same time (late January 1996) and correspond to two different aircraft types (B-727 and B-777). Differential temperatures obtained from thermocouple readings were the following: -0.06 ^{o}C (-0.1 ^{o}F) for B-727 and –2.5 ^{o}C (-4.5 ^{o}F) for B-777. A coefficient of thermal expansion of $9.9\times10^{-6}/^{o}$C ($5.5\times10^{-6}/^{o}$F) was assumed for both analyses.

Deflections at the LVDT locations were calculated using ILLI-SLAB for each position of the gear as it moved through the instrumented section of the runway. Slab deflections due to temperature were subtracted from ILLI-SLAB results for combined temperature and loading. The reason for this subtraction of initial temperature curl is because the dynamic LVDT's store only the relative deflections due to passage of the gear whereas the ILLI-SLAB results report absolute displacement from an initial flat slab condition. This analysis demonstrated that temperature distribution through the slab had to be included in the structural analysis due to its effect on the initial slab shape and ultimately on the measured and calculated deflections. This is extremely important when there is significant separation between the slab and foundation layers, such as cases when the differential temperature between top and bottom of the slab is very high.

Figure 4 shows the gear path relative to the position of the LVDT's for both events analyzed. The sensors having the complete time-history of deflections in each case are shown in bold. The determination of each aircraft gear path is shown in Rufino *et al.* (2001). The average gear path of wide body aircraft, such as B-777, was on top of the longitudinal joint, whereas the average gear path of smaller aircraft, such as B-727, was in the interior portion of the slab. Therefore, the two selected events represent typical aircraft passes of the selected aircraft types. In order to compare responses, two sensors (SDD14 and SDD16) that have complete time-history of deflections were selected.

An LTE value of 25% was selected as the standard value for the sensitivity analysis comparison based on HWD results. LTE was used in ILLI-SLAB by means of an aggregate interlock factor (AGG) taken from a relationship proposed by Ioannides and Korovesis (1990b). The authors arranged three parameters (AGG and $k\ell$) from a chart proposed by Tabatabaie and Barenberg (1980) into one dimensionless independent variable ($AGG/k\ell$), resulting in an S-shape curve for LTE. This curve allows the selection of an AGG value to achieve a desired LTE based on a circular plate deflection for a given pavement structure.

SDD14 is located at slab D2, 0.31 m (12 in) from both transverse and longitudinal joints, near the slab corner (see Figure 4). SDD16 is located at slab D3, 0.31 m (12 in) from the transverse joint and 1.52 m (60 in) from the longitudinal joint between slabs C and D as shown in Figure 4. The LTE was re-calculated after running the ILLI-SLAB program to determine if 25% LTE was an appropriate estimate from the HWD results. Right before or after the B-727 crossed the transverse joint, the LTE was 42% at the SDD14 location (corner) and 28% at the SDD16 location (transverse joint), assuming a k-value of 81.4 MPa/m (300 psi/in). For the B-777, the ILLISLAB LTE was 37% for both sensor locations. These values were calculated by dividing the deflection on the unloaded side by the deflection on the loaded side at the sensor location of interest.

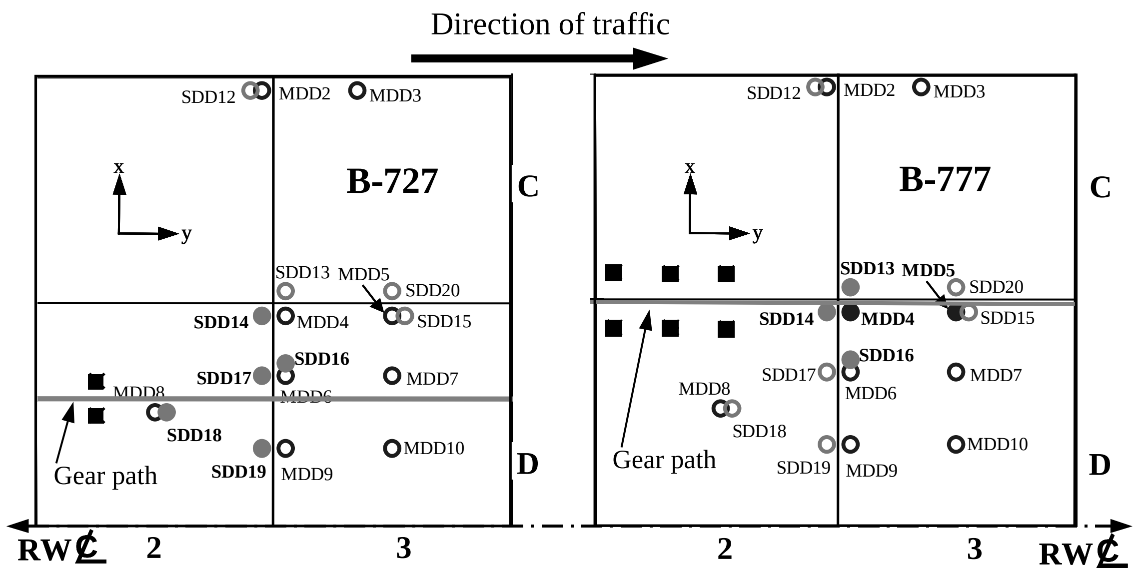

Figure 4. Gear path relative to the location of the sensors

Figure 5 shows the deflection profiles of the two events analyzed when the center of the gear is on top of sensors SDD14 and SDD16. Using an approximation of the geometric procedure proposed by Brill (2000), the LTE can be estimated from the actual aircraft pass. For the chosen B-727 event, the LTE at the transverse joint is 27%, whereas the LTE at the corner is 49%. For the B-777, however, the LTE does not change much: 32% at the corner and 37% at the transverse joint. Therefore, the ILLI-SLAB AGG factor assumed initially, realistically reproduces the change in the measured LTE for different aircraft at different locations near the joint. This demonstrates that the change in field LTE along the joint depends on the relative position of the load with respect to the point of interest, as well as the load configuration (B-777 vs. B-727).

Figure 6 shows a sensitivity analysis of k-value based on SDD14 readings for the B-727 and B-777 and Figure 7 shows this sensitivity analysis based on SDD16 readings. The total load was 777 kN (174,594 lbf) for the B-727 and 1933 kN (434,645 lbf) for the B-777, which represent 92 and 80 % of their respective maximum allowable takeoff weight according to Boeing (http://www.boeing.com/). The present analysis assumed that 47.5% of the gross load was carried by each main gear. Dividing the gear load by the number of wheels in each case produces wheel loads of 184 kN (41,466 lbf) for B727 and 153 kN (34,409 lbf) for B-777. The B-777 has approximately the same calculated deflections as the B-727 for a transverse edge position when one wheel of the B-777 gear is about 83 cm (32.5 in) away from the sensor and one wheel of B-727 is only 10 cm (4.0 in) from the sensor.

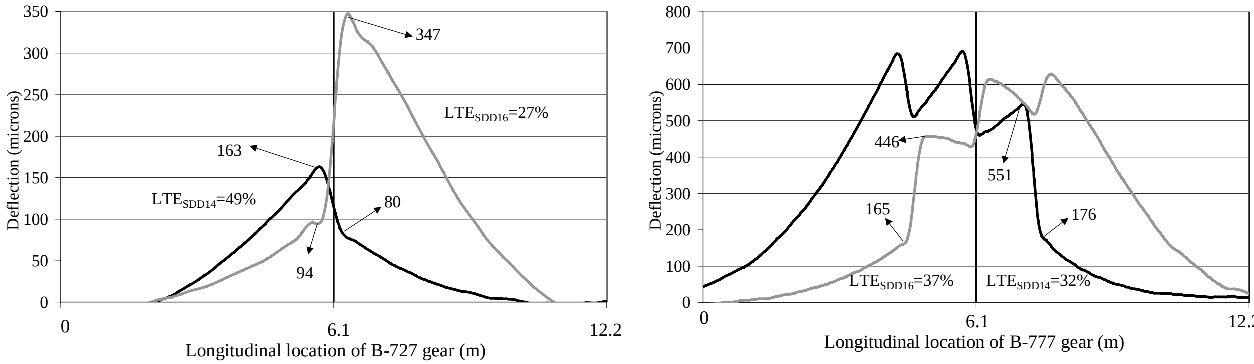

Figure 5. Estimation of LTE based on actual aircraft pass

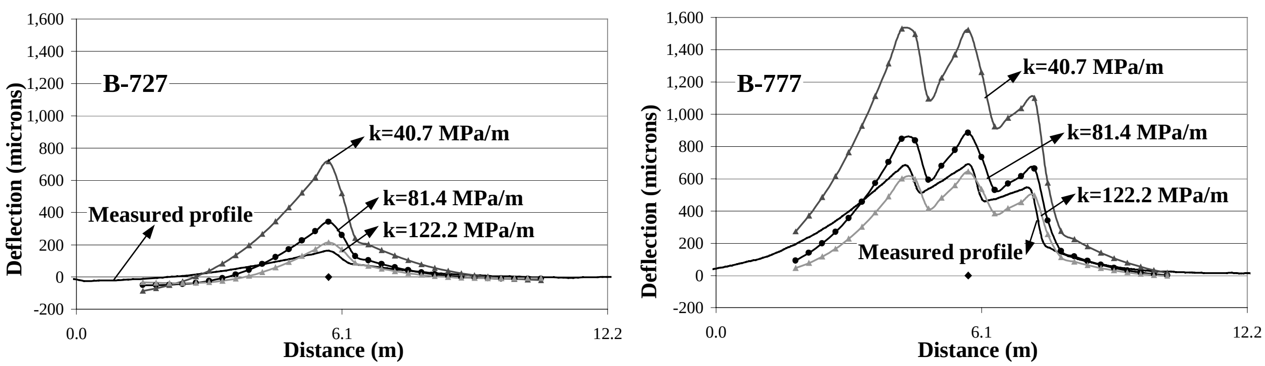

Figure 6. Sensitivity analysis of k-value for a corner sensor (SDD14)

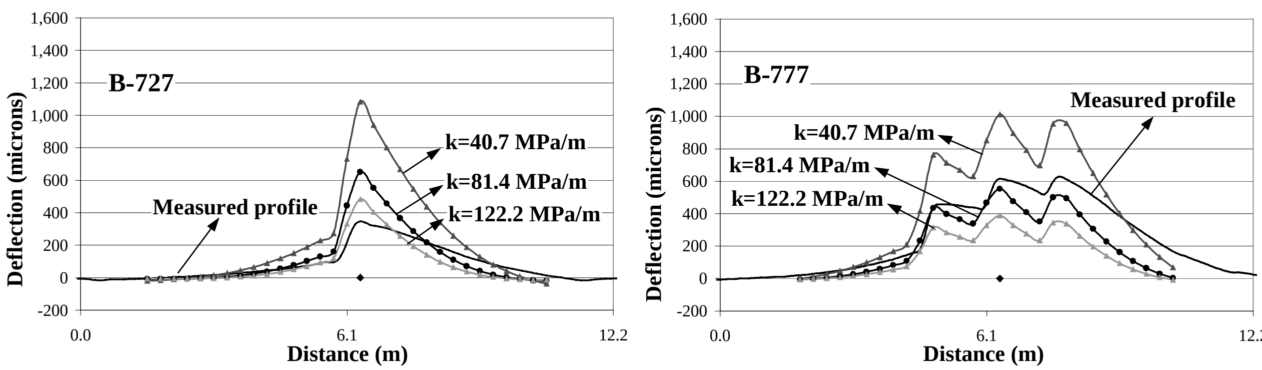

Figure 7. Sensitivity analysis of k-value for a transverse joint sensor (SDD16)

Figures 6 and 7 show how sensitive slab deflections are to foundation support values (k-value). Reducing the selected standard k-value from 81.4 to 40.7 MPa/m (300 to 150 psi/in) effectively doubled the deflections. However, increasing the k-value by 50 percent (81.4 to 122.2 MPa/m or 300 to 450 psi/in) did not affect the deflections as much when compared to a 50 percent reduction in k-value. This is because deflections are more sensitive to low values of k. When the same k-value for both events was used, ILLI-SLAB over predicted the measured deflections for the B-727. For B-777, the corner deflections were predicted reasonably well, but the deflections at the transverse joint were under predicted for the standard case values (LTE = 25% and k-value =300 psi/in). More accurate values for the foundation k or modulus are needed for better predictions between the measured and calculated responses. Furthermore, without a better estimate of k-value, other factors affecting the deflection are masked by the variation of deflection with k-value. Estimation of k-value from empirical correlations can give significant deviation from the measured k-value in the field after construction. In the last section of the paper, reasons for measured versus calculated response discrepancies will be discussed and potential sources for error will be identified.

Figure 8 shows a sensitivity analysis of LTE based on SDD14 sensor readings (corner position), whereas Figure 9 shows the same sensitivity analysis but based on SDD16 sensor readings (transverse joint position). Figures 8 and 9 show that varying LTE at the both joints significantly affects the shape of the deflection profile, along with the peak value of the response. As expected, higher LTE produced a lower peak deflection. Improving the prediction of LTE versus time of day and time of year will definitely increase the ability to match measured field deflections. For a k-value of 81 MPa/m (300 psi/in), the measured deflections in Figures 8 and 9 for three out of four cases fell below the calculated deflections, suggesting a higher k-value is needed especially since the LTE with HWD was measured at approximately 25%.

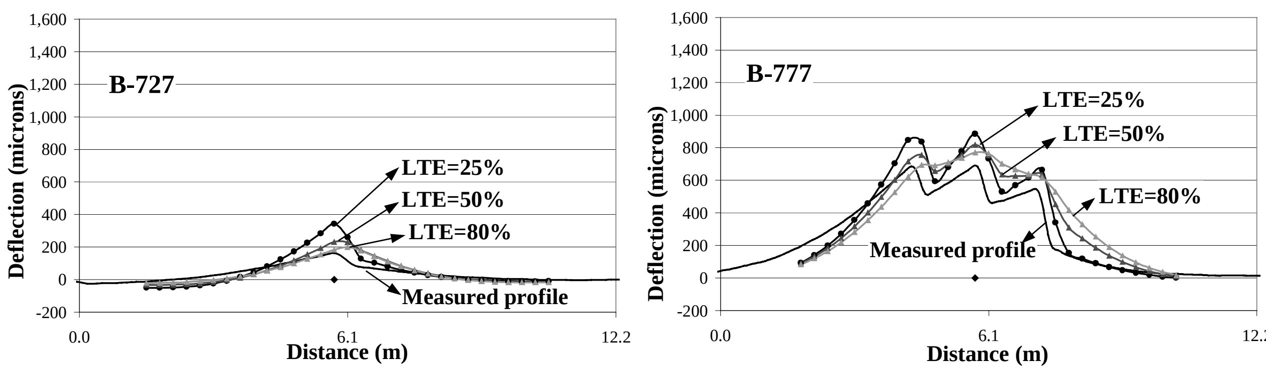

Figure 8. Sensitivity analysis of LTE for SDD14 (corner)

Figure 10 shows a sensitivity analysis of the transverse position of the load based on SDD14 sensor reading (corner). The sensitivity analysis on lateral gear path distribution assumed the calculated gear path was the actual gear path with potential for ±0.31 m (±1.0 ft) of position error. Figure 11 shows this sensitivity analysis based on SDD16 sensor reading (transverse joint). Figures 10 and 11 demonstrate that the lateral load location relative to the sensor has less than a 10 percent effect on the calculated deflection for ±0.31 m from the apparent load location. The corner loading response is more sensitive to lateral position than the response at the transverse joint. The lateral position of the gear relative to the joint was the second most sensitive parameter looked at in this study. The calculated responses for three out of the four cases overestimated the measured responses suggesting the k-value estimation may be the most overriding factor in predicting surface deflections.

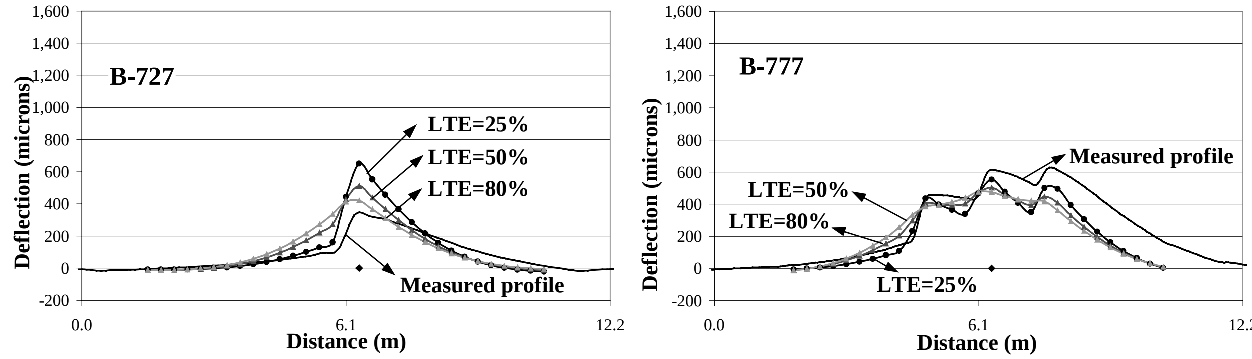

Figure 9. Sensitivity analysis of LTE for SDD16 (joint)

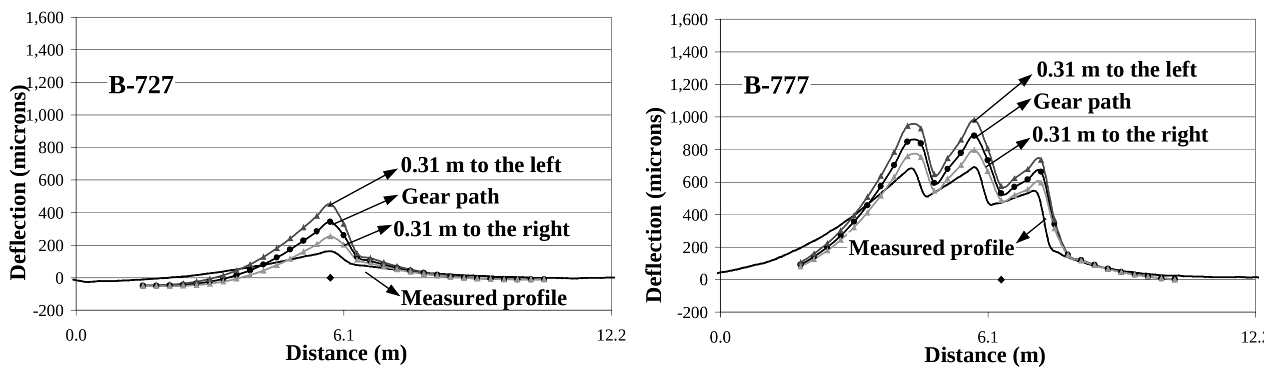

Figure 10. Sensitivity analysis of lateral load location for SDD14 (corner)

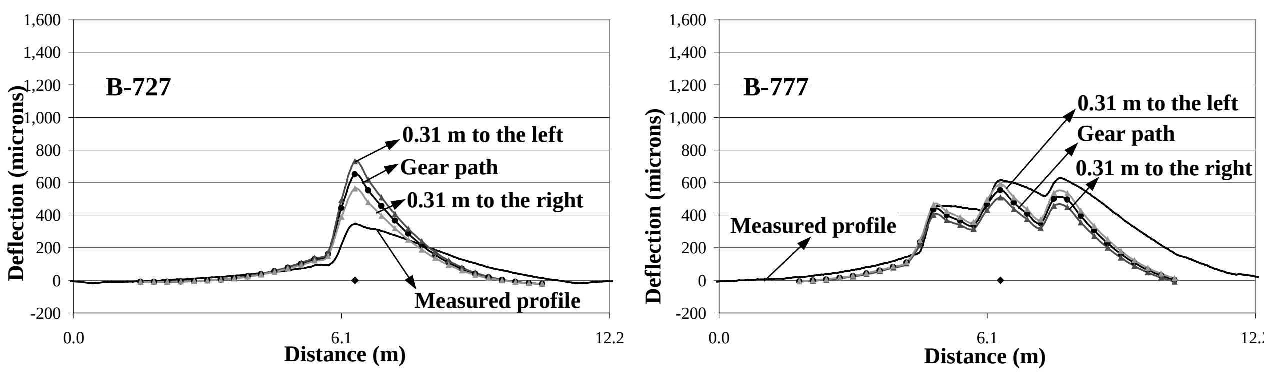

Figure 11. Sensitivity analysis of lateral load location wander for SDD16 (joint)

Figure 12 shows the effect of gear load level on deflections based on SDD14 sensor (corner location) and Figure 13 shows the same effect based on the readings of SDD16 (transverse joint location). The gear load level was varied +10% and –10% of the expected gear load (47.5% of the total load, as discussed before). Figures 12 and 13 show that varying the gear load affects the calculated deflection by the same percentage for both aircraft type, but still under predicts the measured deflections using the standard case values of LTE of 25% and k-value of 81 MPa/m (300 psi/in).

Table 1 shows a summary of the sensitivity analysis for calculated peak values deflections relative to the peak values of the standard case. The parameters of the standard case are: k=81.4 MPa/m, LTE=25%, load lateral position is equal to gear path and gear load level is 47.5% of the total load. It is observed that k-value is the most sensitive parameter in this analysis, especially with variation from 40.7 to 81.4 MPa/m (150 to 300 psi/in). Variation in LTE from 25 to 80% can reduce deflections by 60% for B-727. However, B-777 was less sensitive to changes in LTE. An offset of 0.31 m (1 ft) to the right or to the left has an effect of approximately 10% on deflections, except for B-727 triggering the corner sensor (SDD14) when the change in deflection is approximately 30%. The effect of load level on deflection is approximately proportional to the applied load due to the low thermal gradient in the slab.

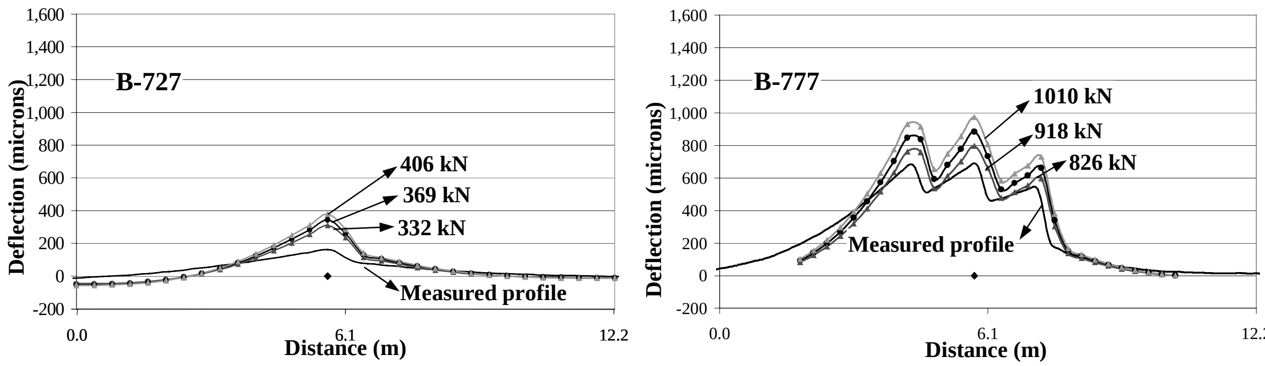

Figure 12. Sensitivity analysis for load level for SDD14 (corner)

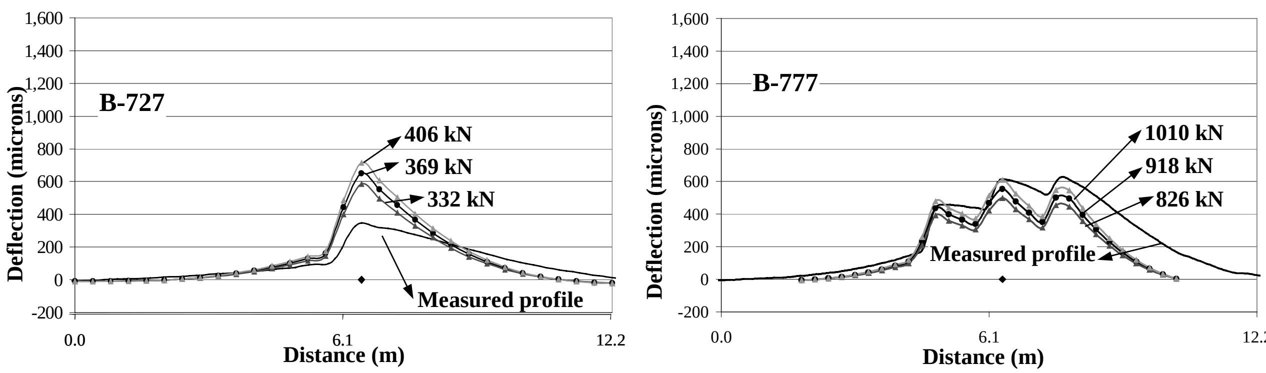

Figure 13. Sensitivity analysis for load level SDD16 (joint)

POTENTIAL ERROR SOURCES FOR CALCULATED DEFLECTION AT DIA

Several potential error sources were explored for determining why measured and calculated responses may not be in agreement. The most likely reason is inadequate information on the subgrade k-value and the depth of bedrock. A low strength subgrade can be significantly stiffened if a rigid layer is close to the surface (<10 ft.). Lateral position of the gear can also affect the calculated response along with the LTE at the joint. The bonding condition between the slab and base layer will affect the magnitude of the calculated deflection. Although the slab-base interface has a bond-breaker, the measured responses suggest it may be behaving like a bonded condition for the cases presented.

Table 1. Summary of the sensitivity analysis relative to the standard case

Cases analyzed		B-727					B-777				
		SDD14	SDD16	SDD17	SDD18	SDD19	MDD4	MDD5	SDD13	SDD14	SDD16
k-value (MPa/m)	40.7	2.1	1.7	1.6	1.5	1.7	1.7	1.8	1.7	1.7	1.8
	122.2	0.6	0.7	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7
LTE (%)	50	0.7	0.8	0.8	1.0	0.8	0.9	1.0	0.9	0.9	0.9
	80	0.6	0.6	0.7	1.0	0.7	0.9	1.0	0.8	0.9	0.9
Load lateral position	-0.31 m	1.3	1.1	1.1	0.9	0.8	1.1	1.1	0.9	1.1	0.9
	+0.31 m	0.7	0.9	0.9	1.0	1.1	0.9	0.9	1.1	0.9	1.1
Load level	-10%	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	+10%	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1

Other potential error sources are the following: initial slab warping, actual tire pressure, gear load, non-uniform gear load and tire pressure, and sensor error. An average constant aircraft speed was assumed to match the calculated and measured deflections. Depending upon the acceleration rate of the aircraft, the shape of the calculated deflection profile at the sensor location can also change. All these potential sources of error can add up, making it difficult to match measured and calculated responses.

SUMMARY AND CONCLUSIONS

This study presents a sensitivity analysis of deflections for typical wander patterns of two critical aircraft: B-727 and B-777. The gear path analyzed for the B-727 was in the middle of the slab and the B-777 gear path straddled the longitudinal joint. Some of the conclusions that can be drawn are as follows:

- Measured and calculated predicted deflections can be matched to a reasonable accuracy if the appropriate input values are assumed. A sensitivity analysis of some factors that can affect the accuracy of such analysis showed that a reliable estimate of k-value is critical. Load transfer efficiency, lateral position, and load level also affect the calculated deflections. Some other factors that will affect the predictions but were not included in this study are: initial slab warp, slab-base bonding condition, tire pressure and gear load variation, non-uniform gear load and tire pressure, and sensor error.
- Since k-value is the most critical parameter when matching measured and calculated deflections, a methodology to best estimate k-value or subgrade modulus needs to be developed for the DIA data analysis project. Estimation of k-value from HWD testing and backcalculation of the k-value based on actual aircraft passes are currently underway.

- The complexity involved in the data processing and analysis requires a significant amount of time and effort. Response data from different sensors need to be matched with theoretical models for future design improvements. Important input parameters in the analysis such as location of the load, subgrade modulus, joint load transfer, etc. need to be estimated with sufficient accuracy in order to determine if errors are associated with the model or *in-situ* material property quantifications. Additional effort should be made to better estimate the input parameters through material testing and additional field monitoring.

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