RUNWAY KEEL SECTION REPLACEMENT IN THE MIDDLE EAST
(A CASE HISTORY)

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INTRODUCTION

Grading of airfield pavements has always been a challenge to Engineers as multiple constraints need to be considered and evaluated to properly design longitudinal and transverse gradients. Analysis is made more difficult in the design of pavement reconstruction and rehabilitation as recommended improvements often result in partial pavement removal and replacement requiring the new pavement to tie into existing pavement elevations. This paper focuses on one of the more difficult pavement grading analysis: grading the removal and replacement of an existing runway keel section of an older runway in the touchdown zone area that was constructed with inconsistent gradients not adhering to current criteria.

The design alternate analysis reviewed four options for the longitudinal and transverse design: design to existing grades, best fit longitudinal slope, elevated longitudinal slope, and elevated longitudinal slope with constant transverse gradient for inner 20m. An Aircraft simulation program to simulate aircraft response on the proposed grading option was analyzed to insure that the grades would produce an acceptable aircraft response. The keel replacement project was accomplished under an Army Corps of Engineers' contract in support of the U.S. Air Force operations at an Expeditionary Airfield.

Runway 14-32 is 62.5m wide, 3502m long, and is constructed of plain concrete pavement with typical panel dimensions 3.81m by 4.12m, approximate 12 inch (30cm) thickness, over a granular base course. The runway geometrical dimensions are capable of supporting wide body aircraft, however, the pavement section was designed for smaller commuter and fighter aircraft. As a result of age and current usage by large aircraft the pavement was experiencing rapid deterioration which initiated the project to replace the center keel section, approximately 3,300 feet (1,000m) by 98 feet (30m) wide, with 20 inch (52cm) thick concrete pavement. The beginning of the 3,300 foot (1,000m) length keel section replacement is located 498 feet (152m) from the runway threshold.

The existing pavement was surveyed and found to have irregular transverse and longitudinal slopes/grades; the challenge being to design the pavement grades to meet applicable criteria for longitudinal and transverse cross slopes while tying into existing pavements on all four sides. In all of the design grading options reviewed tying the proposed keel concrete surfaces into the existing grades would result in transitional surfaces that could produce unacceptable aircraft response. A keel replacement requires that the new pavement tie into existing pavement both longitudinally and transversely which results in design constraints that raise the issue of roughness. The primary reason for constructing and maintaining a smooth (consistent gradient) airport pavement is to minimize the surface irregularities that influence aircraft response during taxi, takeoff and landing. Aircraft simulation technology was used in this project to insure that adequate gradients would be achieved and corrections to the concrete after placement could be avoided. Smoothness was a concern for two reasons;

1. Because of the transition areas where the keel section replacement meets the existing pavement longitudinally and,

2. Because it was necessary to vary the cross-sectional drainage slopes to meet existing pavement outside the keel section replacement area. Since the transverse cross slopes were

continually varying, the resulting longitudinal profile had undulations due to these design constraints.

Pavement roughness is the undulations in the surface profile that adversely affect the dynamic response of the aircraft that use those pavements. It is not texture. Pavement roughness can be broken into three categories.

1. Shock is the result of encountering a sharp change in elevation such as a step bump, a raised slab or spall. These are very short wavelength bumps and dips.

2. Short wavelength roughness is undulations in the profile that does not excite the aircraft as whole, just that particular landing gear.

3. Long wavelength roughness is undulations in the profile that cause the aircraft to respond as a whole. What happens at the main landing gear will cause a response at the nose gear and vice versa.

Types 2 and 3 were the primary interest in this analysis.

PROJECT CRITERIA

The grading criteria used in the analysis of the Runway 14/32 keel replacement are based on the project Request for Proposal (RFP) specifications and UFC 3-260-01.

Table 1.
Project Base Criteria – UFC 3-260-01[a]

Description	Criteria/Comment
Runway centerline profile	Maximum rate of grade change shall not exceed 0.167% per 30 linear meters. Maximum rate of longitudinal grade change is produced by vertical curves having 180 meters [600 foot] lengths for each percent of algebraic difference between the two grades.)
Longitudinal Runway grade changes	No grade change is to occur less than 900 m [3,000 ft] from the runway end.
Runway transverse section	Runway pavement shall have a transverse slope from the centerline. Slope shall be a minimum of 1.0% and a maximum of 1.5%. Selected transverse grade is to remain constant for length and width of runway, except at or adjacent to runway intersections where pavement surfaces must be warped to match abutting pavements.

[a]UFC – Unified Facilities Criteria

Table 2.
FAA Criteria – AC 150/5300-13

Criteria[b]	Description
Runway centerline profile	Maximum longitudinal grade 1.5%. Longitudinal grades may not exceed 0.8% in the 1st and last quarter of the runway. Maximum allowable grade change is 1.5%
Longitudinal Runway	The length of the vertical curve is a minimum of 1000 feet (300m)

Table 2.
FAA Criteria – AC 150/5300-13

Criteria[b]	Description
grade changes	multiplied by the grade change in percent. The minimum allowable distance between the points of intersection of vertical curves is 1000 feet (300m) multiplied by the sum of the grade changes in percent associated with the two vertical curves.
Runway transverse section	Runway pavement shall have a transverse slope from the centerline. Slope shall be a minimum of 1.0% and a maximum of 1.5%.

[b]based on Aircraft approach categories C & D

Although the project criteria is based on UFC criteria Table 2 is presented to show the comparison between UFC and FAA criteria for runway gradients. The FAA and UFC have similar gradient requirements with the exception of the FAA being more conservative with regard to runway vertical curve lengths.

EXISTING CONDITIONS

An on-the-ground topographic survey was performed to identify the Runway 14/32 centerline location/elevations and location/elevations at the pavement tie at approximately 49 feet (15m) each side of the runway center line. Elevations/location survey points were taken at approximately 50 foot intervals for the length of the repair section and beyond to identify the existing grades.

The survey data showed the majority of the runway cross slope gradients to be between 0.8% and 1% with irregular transverse/longitudinal slopes and grades which is close but less than the UFC requirement of a minimum 1% cross slope with multiple areas under 0.9%. The runway longitudinal slope varies along the runway centerline generally in a negative sloping direction from south to north. These differences and varying pavement elevations are expected due to construction techniques/tolerances and due to the age of the pavement.

GRADING ALTERNATIVES

With the general understanding that there are limited re-grading options available when designing pavement reconstruction to match existing pavement grades, located approximately 49 feet (15m) from the runway centerline, the available alternates reviewed are listed below. The grading alternates were analyzed using digital terrain models and the output tables discussed herein have been modified for general discussion purposes.

Alternate 1 - Reconstruct the pavement back to existing grades

Alternate 2 - Reconstruct the pavement with a best fit constant gradient longitudinal centerline

Alternate 3 - Reconstruct the pavement with a constant gradient elevated longitudinal centerline

Alternate 4 - Reconstruct the pavement with a constant gradient elevated longitudinal centerline and constant gradient transverse cross slope.

Alternate 1Reconstruct Pavement back to Existing Grades

Reconstructing the pavement back to the existing surveyed elevations was briefly reviewed but discounted as the existing pavement elevations do not generally meet the UFC requirements for a one percent minimum transverse cross slope, the longitudinal profile varies from station to station, as does the transverse slopes, reconstruction back to variable pavement elevations would be difficult, and construction tolerances may exacerbate the existing pavement elevation differentials.

Alternate 2 - Reconstruct Pavement with Best Fit Longitudinal Profile

An option to reconstructing back to existing grades with the least change to existing elevations and gradients would be to design a best fit constant gradient from the beginning of the demolition works (Station 0+152.692m) to the end of the reconstruction (Station 1+221.375m). This would result in a smooth linear longitudinal profile along the reconstruction alignment but would have limited/no improvement to the transverse cross slopes which are generally under one percent. Table 3 below shows the relative differential in existing and proposed runway center line elevations. Table 4 shows the relative differential in the longitudinal centerline elevations by using a uniform longitudinal runway center line slope of -0.011% in the reconstruction area.

Table 3.
Best Fit Profile

STATION (m)	EXISTING CENTER LINE (m)	PROPOSED CENTER LINE (m)	DIFFERENTIAL (m)
152.692	48.967	48.967	0
198.108	48.968	48.962	-0.006
297.185	48.959	48.952	-0.007
396.311	48.983	48.941	-0.042
495.363	48.946	48.93	-0.016
594.461	48.925	48.92	-0.005
705.937	48.898	48.908	0.01
804.489	48.9	48.897	-0.003
903.551	48.89	48.887	-0.003
1002.616	48.873	48.876	0.003
1101.632	48.872	48.866	-0.006
1200.685	48.842	48.855	0.013
1221.375	48.853	48.853	0

As the concept is to straight line between the beginning and end points of the runway repair area the existing transverse cross slopes will not be changed by any significant difference with most of the slopes remaining under one percent. Although the runway longitudinal centerline will be a single gradient the relative station to station transverse slope gradients will remain variable, under one percent, and non uniform.

Table 4.
Alternate 2 –Best Fit Profile

		SLOPE FROM 15M TO 18M			SLOPE FROM CL TO 15M				SLOPE FROM CL TO 15M			SLOPE FROM 15M TO 18M				
STATION	SLOPE DIFFERENTIAL CL TO 15M, 15M TO 18M LEFT	SLOPE	ELV.	DISTANCE TO CL	SLOPE	ELV.	DISTANCE TO CL	PROPOSED CENTER LINE	DISTANCE TO CL	ELV.	SLOPE	DISTANCE TO CL	ELV.	SLOPE	SLOPE CL LOGITUDINAL	SLOPE DIFFERENTIAL CL TO 15M, 15M TO 18M RIGHT
152.692	0.093%	0.804%	48.802	18.77	0.898%	48.832	15.04	48.967	15.02	48.826	0.939%	18.78	48.792	0.904%		0.034%
															-0.01101%	
198.108	-0.195%	0.960%	48.811	18.78	0.765%	48.847	15.03	**48.962**	15.01	48.832	0.866%	18.77	48.798	0.904%		-0.038%
															-0.01009%	
297.185	-0.256%	1.135%	48.777	18.82	0.878%	48.820	15.03	**48.952**	15.02	48.819	0.885%	18.79	48.789	0.796%		0.090%
															-0.01110%	
396.311	-0.475%	1.273%	48.773	18.80	0.798%	48.821	15.03	**48.941**	15.03	48.809	0.878%	18.79	48.771	1.011%		-0.132%
															-0.01111%	
495.363	-0.038%	0.904%	48.766	18.77	0.866%	48.800	15.01	**48.930**	15.05	48.807	0.817%	18.80	48.778	0.773%		0.044%
															-0.01009%	
594.461	-0.053%	0.957%	48.748	18.79	0.905%	48.784	15.03	**48.920**	15.04	48.773	0.977%	18.79	48.741	0.853%		0.124%
															-0.01076%	
705.937	-0.050%	0.987%	48.730	18.80	0.937%	48.767	15.05	**48.908**	15.02	48.771	0.912%	18.80	48.742	0.767%		0.145%
															-0.01116%	
804.489	0.014%	0.984%	48.710	18.79	0.998%	48.747	15.03	**48.897**	15.02	48.755	0.945%	18.79	48.720	0.928%		0.017%
															-0.01009%	
903.551	-0.203%	1.114%	48.708	18.80	0.912%	48.750	15.03	**48.887**	15.01	48.756	0.873%	18.78	48.720	0.955%		-0.082%
															-0.01110%	
1002.616	-0.091%	1.043%	48.694	18.76	0.952%	48.733	15.02	**48.876**	15.02	48.730	0.972%	18.78	48.700	0.798%		0.174%
															-0.01010%	
1101.632	-0.263%	1.197%	48.681	18.76	0.933%	48.726	15.00	**48.866**	15.05	48.737	0.857%	18.80	48.702	0.933%		-0.076%
															-0.01111%	
1200.685	0.185%	0.822%	48.673	18.76	1.007%	48.704	14.99	**48.855**	15.03	48.712	0.951%	18.80	48.676	0.955%		-0.003%
															-0.00967%	
1221.375	-0.292%	1.176%	48.676	18.77	0.885%	48.720	15.03	48.853	15.01	48.705	0.986%	18.78	48.670	0.928%		0.058%

Alternate 3 - Reconstruct Pavement with an Elevated Longitudinal Profile

As an alternate to obtain transverse cross slopes to UFC criteria (between 1 and 1.5 percent) the center line was lifted slightly and a single longitudinal runway gradient was used along the repair area (except at the beginning and end where transitions are required to match existing pavement elevations). Table 5 below shows the relative differential in existing and proposed runway center line elevations. Table 6 shows the proposed longitudinal profile at approximate 100m stations along the repair alignment. Transitions at the beginning and end of the repair area are well within the UFC and RFP required maximum rate of grade change of 0.167% per 30 linear meters.

Table 5
Raised Profile Centerline

STATION	CENTER LINE	PROPOSED CENTER LINE	DIFFERENTIAL
152.692	48.967	48.967	0
198.108	48.968	49.007	0.039
297.185	48.959	48.994	0.035
396.311	48.983	48.981	-0.002
495.363	48.946	48.968	0.022
594.461	48.925	48.955	0.03
705.937	48.898	48.94	0.042
804.489	48.9	48.927	0.027
903.551	48.89	48.914	0.024
1002.616	48.873	48.901	0.028
1101.632	48.872	48.888	0.016
1200.685	48.842	48.875	0.033
1221.375	48.853	48.853	0

The average elevation lift along the center line is approximately 2.5cm and results in an increase in the majority of the runway transverse slopes from less than 1 percent to approximately 1.1 percent. The lift in the vertical profile, however, will not smoothen out the transverse variable grades as the existing elevations remain variable at the pavement edge tie in locations.

Table 6.
Alternate 3- Raised Profile Centerline

STATION	SLOPE DIFFERENTIAL CL TO 15M, 15M TO 18M LEFT	SLOPE FROM 15M TO 18M		SLOPE FROM CL TO 15M		PROPOSED CENTER LINE	SLOPE FROM CL TO 15M		SLOPE FROM 15M TO 18M		SLOPE CL LOGITUDINAL	SLOPE DIFFERENTIAL CL TO 15M, 15M TO 18M RIGHT
		SLOPE	ELV.	SLOPE	ELV.		ELV.	SLOPE	ELV.	SLOPE		
152.692	0.093%	0.805%	48.802	0.898%	48.832	**48.967**	48.826	0.939%	48.792	0.904%		0.034%
											0.08807%	
198.108	0.105%	0.960%	48.811	1.065%	48.847	**49.007**	48.832	1.166%	48.798	0.904%		0.262%
											-0.01312%	
297.185	0.023%	1.135%	48.777	1.158%	48.820	**48.994**	48.819	1.165%	48.789	0.796%		0.369%
											-0.01311%	
396.311	-0.209%	1.273%	48.773	1.065%	48.821	**48.981**	48.809	1.144%	48.771	1.011%		0.134%
											-0.01312%	
495.363	0.215%	0.904%	48.766	1.119%	48.800	**48.968**	48.807	1.070%	48.778	0.773%		0.296%
											-0.01312%	
594.461	0.180%	0.957%	48.748	1.138%	48.784	**48.955**	48.773	1.210%	48.741	0.853%		0.357%
											-0.01346%	
705.937	0.163%	0.987%	48.730	1.150%	48.767	**48.940**	48.771	1.125%	48.742	0.767%		0.358%
											-0.01319%	
804.489	0.214%	0.984%	48.710	1.198%	48.747	**48.927**	48.755	1.145%	48.720	0.928%		0.217%
											-0.01312%	
903.551	-0.023%	1.114%	48.708	1.091%	48.750	**48.914**	48.756	1.053%	48.720	0.955%		0.098%
											-0.01312%	
1002.616	0.076%	1.043%	48.694	1.119%	48.733	**48.901**	48.730	1.138%	48.700	0.798%		0.341%
											-0.01313%	
1101.632	-0.117%	1.197%	48.681	1.080%	48.726	**48.888**	48.737	1.003%	48.702	0.933%		0.070%
											-0.01312%	
1200.685	0.318%	0.822%	48.673	1.141%	48.704	**48.875**	48.712	1.084%	48.676	0.955%		0.130%
											-0.10633%	
1221.375	-0.292%	1.176%	48.676	0.885%	48.720	**48.853**	48.705	0.986%	48.670	0.928%		0.058%

Alternate 4 - Reconstruct Pavement with an Elevated Longitudinal Profile and Uniform Cross Slope

A hybrid to smoothen out the transverse gradient an option to Alternate 3 is to keep the same elevation increase in the longitudinal runway center line gradient and additionally maintain a uniform transverse cross slope for the first 10m on each side of the runway center line (2 new panel widths) and then let the last panel (remaining new 5m panel width) become the variable pavement section to match the existing pavement elevations.

This scenario would result in a smooth longitudinal runway profile and a uniform transverse cross slope for the interior 20m (65 feet) of the runway (10m on each side of the runway center line) with 5m of variable pavement transition on each side. Multiple uniform cross slopes were reviewed to minimize the pavement cross slope differentials between the uniform grade, the transition zone grade, and the existing cross slope grades. Tables 7 and 8 show the results of the 1 percent and 1.1 percent transverse cross slope analysis.

The 1 percent uniform cross slope shows 2 areas where the transition zone panel cross slopes will exceed 1.5 percent with a majority of the transition panels closer to the transverse upper limit slope allowed (1.5% transverse slope) which results in relatively large transverse panel slope differentials: 1 percent slope for 10m, close to 1.35 percent average slope at the transition panel, existing panel slopes at or under 1 percent (0.88% average).

The 1.1 percent uniform cross slope shows 2 areas where the transition zone panels will be under 1 percent with a majority of the transition panels closer to 1.1 percent which results in smaller transverse panel slope differentials: 1.1 percent for 10m, closer to 1.1 percent average slope at the transition panel, existing panel slopes at or under 1 percent (0.88% average). Table 9 shows the relative differentials in the slopes between the 1 and 1.1 percent transverse cross slope alternates.

Table 7.
Alternate 4 – Elevated Longitudinal Profile and Uniform 1% Cross Slope

STATION	SLOPE DIFFERENTIAL 10M TO 15M, 15M TO 18M LEFT	SLOPE DIFFERENTIAL CL TO 10M, 10M TO 15M LEFT	SLOPE 15M TO 18.7M	SLOPE 10M TO 15M LEFT	SLOPE CL TO 10M LEFT	18.7M LEFT	15M LEFT	EXACT DIST. TO CL	10M LEFT	PROPOSED CENTER LINE	10M RIGHT	EXACT DIST. TO CL	15M RIGHT	18.7M RIGHT	SLOPE CL TO 10M RIGHT	SLOPE 10M TO 15M RIGHT	SLOPE 15M TO 18.7M	SLOPE CL LOGITUDINAL	SLOPE DIFFERENTIAL CL TO 10M, 10M TO 15M RIGHT	SLOPE DIFFERENTIAL 10M TO 15M, 15M TO 18M RIGHT
152.692			0.811%			48.802	48.832	15.04	48.877	48.967	48.877	15.02	48.826	48.792			0.919%			
																		0.08807%		
198.108	0.233%	-0.193%	0.960%	1.193%	1.000%	48.811	48.847	15.03	48.907	**49.007**	48.907	15.01	48.832	48.798	1.000%	1.497%	0.904%		-0.497%	0.593%
																		-0.01312%		
297.185	0.337%	-0.471%	1.135%	1.471%	1.000%	48.777	48.82	15.03	48.894	**48.994**	48.894	15.02	48.819	48.789	1.000%	1.494%	0.796%		-0.494%	0.698%
																		-0.01311%		
396.311	-0.080%	-0.193%	1.273%	1.193%	1.000%	48.773	48.821	15.03	48.881	**48.981**	48.881	15.03	48.809	48.771	1.000%	1.431%	1.011%		-0.431%	0.421%
																		-0.01312%		
495.363	0.453%	-0.357%	0.904%	1.357%	1.000%	48.766	48.8	15.01	48.868	**48.968**	48.868	15.05	48.807	48.778	1.000%	1.208%	0.773%		-0.208%	0.435%
																		-0.01312%		
594.461	0.454%	-0.412%	0.957%	1.412%	1.000%	48.748	48.784	15.03	48.855	**48.955**	48.855	15.04	48.773	48.741	1.000%	1.627%	0.853%		-0.627%	0.774%
																		-0.01346%		
705.937	0.459%	-0.446%	0.987%	1.446%	1.000%	48.73	48.767	15.05	48.84	**48.94**	48.84	15.02	48.771	48.742	1.000%	1.375%	0.767%		-0.375%	0.607%
																		-0.01319%		
804.489	0.606%	-0.590%	0.984%	1.590%	1.000%	48.71	48.747	15.03	48.827	**48.927**	48.827	15.02	48.755	48.72	1.000%	1.434%	0.928%		-0.434%	0.506%
																		-0.01312%		
903.551	0.158%	-0.272%	1.114%	1.272%	1.000%	48.708	48.75	15.03	48.814	**48.914**	48.814	15.01	48.756	48.72	1.000%	1.158%	0.955%		-0.158%	0.203%
																		-0.01312%		
1002.616	0.312%	-0.355%	1.043%	1.355%	1.000%	48.694	48.733	15.02	48.801	**48.901**	48.801	15.02	48.73	48.7	1.000%	1.414%	0.798%		-0.414%	0.616%
																		-0.01313%		
1101.632	0.043%	-0.240%	1.197%	1.240%	1.000%	48.681	48.726	15	48.788	**48.888**	48.788	15.05	48.737	48.702	1.000%	1.010%	0.933%		-0.010%	0.077%
																		-0.01312%		
1200.685	0.601%	-0.423%	0.822%	1.423%	1.000%	48.673	48.704	14.99	48.775	**48.875**	48.775	15.03	48.712	48.676	1.000%	1.252%	0.955%		-0.252%	0.298%
																		-0.10633%		
1221.375			1.189%			48.676	48.72	15.03	48.768	48.853	48.752	15.01	48.705	48.67						

Table 8.
Alternate 4 – Elevated Longitudinal Profile and Uniform 1.1% Cross Slope

STATION	SLOPE DIFFERENTIAL 10M TO 15M, 15M TO 18M LEFT	SLOPE DIFFERENTIAL CL TO 10M, 10M TO 15M LEFT	SLOPE 15M TO 18.7M	SLOPE 10M TO 15M LEFT	SLOPE CL TO 10M LEFT	18.7M LEFT	15M LEFT	EXACT DIST. TO CL	10M LEFT	PROPOSED CENTER LINE	10M RIGHT	EXACT DIST. TO CL	15M RIGHT	18.7M RIGHT	SLOPE CL TO 10M RIGHT	SLOPE 10M TO 15M RIGHT	SLOPE 15M TO 18.7M	SLOPE CL LOGITUDINAL	SLOPE DIFFERENTIAL CL TO 10M, 10M TO 15M RIGHT	SLOPE DIFFERENTIAL 10M TO 15M, 15M TO 18M RIGHT
152.692			0.811%			48.802	48.832	15.04	48.877	48.967	48.877	15.02	48.826	48.792			0.919%			
																		0.08807%		
198.108	0.034%	0.106%	0.960%	0.994%	1.100%	48.811	48.847	15.03	48.897	**49.007**	48.897	15.01	48.832	48.798	1.100%	1.297%	0.904%		-0.197%	0.393%
																		-0.01312%		
297.185	0.138%	-0.172%	1.135%	1.272%	1.100%	48.777	48.82	15.03	48.884	**48.994**	48.884	15.02	48.819	48.789	1.100%	1.295%	0.796%		-0.195%	0.499%
																		-0.01311%		
396.311	-0.279%	0.106%	1.273%	0.994%	1.100%	48.773	48.821	15.03	48.871	**48.981**	48.871	15.03	48.809	48.771	1.100%	1.233%	1.011%		-0.133%	0.222%
																		-0.01312%		
495.363	0.253%	-0.058%	0.904%	1.158%	1.100%	48.766	48.8	15.01	48.858	**48.968**	48.858	15.05	48.807	48.778	1.100%	1.010%	0.773%		0.090%	0.237%
																		-0.01312%		
594.461	0.255%	-0.113%	0.957%	1.213%	1.100%	48.748	48.784	15.03	48.845	**48.955**	48.845	15.04	48.773	48.741	1.100%	1.429%	0.853%		-0.329%	0.575%
																		-0.01346%		
705.937	0.261%	-0.148%	0.987%	1.248%	1.100%	48.73	48.767	15.05	48.83	**48.94**	48.83	15.02	48.771	48.742	1.100%	1.175%	0.767%		-0.075%	0.408%
																		-0.01319%		
804.489	0.408%	-0.292%	0.984%	1.392%	1.100%	48.71	48.747	15.03	48.817	**48.927**	48.817	15.02	48.755	48.72	1.100%	1.235%	0.928%		-0.135%	0.307%
																		-0.01312%		
903.551	-0.040%	0.026%	1.114%	1.074%	1.100%	48.708	48.75	15.03	48.804	**48.914**	48.804	15.01	48.756	48.72	1.100%	0.958%	0.955%		0.142%	0.003%
																		-0.01312%		
1002.616	0.113%	-0.055%	1.043%	1.155%	1.100%	48.694	48.733	15.02	48.791	**48.901**	48.791	15.02	48.73	48.7	1.100%	1.215%	0.798%		-0.115%	0.417%
																		-0.01313%		
1101.632	-0.157%	0.060%	1.197%	1.040%	1.100%	48.681	48.726	15	48.778	**48.888**	48.778	15.05	48.737	48.702	1.100%	0.812%	0.933%		0.288%	-0.121%
																		-0.01312%		
1200.685	0.400%	-0.122%	0.822%	1.222%	1.100%	48.673	48.704	14.99	48.765	**48.875**	48.765	15.03	48.712	48.676	1.100%	1.054%	0.955%		0.046%	0.099%
																		-0.10633%		
1221.375			1.189%			48.676	48.72	15.03	48.768	48.853	48.752	15.01	48.705	48.67						

Table 9
Differential Between 1% and 1.1% Uniform Cross Slopes

	LEFT SIDE (WEST)				RIGHT SIDE (EAST)			
	ALT 4 WITH 1% CROSS SLOPE		ALT 4 WITH 1.1% CROSS SLOPE		ALT 4 WITH 1% CROSS SLOPE		ALT 4 WITH 1.1% CROSS SLOPE	
STA	SLOPE DIFFER. 10M TO 15M, 15M TO 18M LEFT	SLOPE DIFFER. CL TO 10M, 10M TO 15M LEFT	SLOPE DIFFER. 10M TO 15M, 15M TO 18M LEFT	SLOPE DIFFER. CL TO 10M, 10M TO 15M LEFT	SLOPE DIFFER. CL TO 10M, 10M TO 15M RIGHT	SLOPE DIFFER. 10M TO 15M, 15M TO 18M RIGHT	SLOPE DIFFER. CL TO 10M, 10M TO 15M RIGHT	SLOPE DIFFER. 10M TO 15M, 15M TO 18M RIGHT
152.6								
198.1	0.2328%	-0.1928%	0.0340%	0.1060%	-0.4970%	0.5928%	-0.1974%	0.3931%
297.1	0.3366%	-0.4712%	0.1378%	-0.1724%	-0.4940%	0.6983%	-0.1948%	0.4991%
396.3	-0.0804%	-0.1928%	-0.2792%	0.1060%	-0.4314%	0.4208%	-0.1326%	0.2220%
495.3	0.4530%	-0.3573%	0.2534%	-0.0577%	-0.2079%	0.4346%	0.0901%	0.2366%
594.4	0.4541%	-0.4115%	0.2553%	-0.1127%	-0.6270%	0.7737%	-0.3286%	0.5752%
705.9	0.4589%	-0.4455%	0.2609%	-0.1475%	-0.3745%	0.6073%	-0.0753%	0.4081%
804.4	0.6064%	-0.5905%	0.4076%	-0.2917%	-0.4343%	0.5059%	-0.1351%	0.3067%
903.5	0.1583%	-0.2724%	-0.0405%	0.0264%	-0.1577%	0.2028%	0.1419%	0.0032%
1002	0.3118%	-0.3546%	0.1126%	-0.0554%	-0.4143%	0.6165%	-0.1151%	0.4173%
1101	0.0432%	-0.2400%	-0.1568%	0.0600%	-0.0099%	0.0766%	0.2881%	-0.1215%
1200	0.6006%	-0.4228%	0.4002%	-0.1224%	-0.2525%	0.2976%	0.0463%	0.0988%
1221								
SUM	3.5754%	-3.9515%	1.3853%	-0.6614%	-3.9005%	5.2266%	-0.6124%	3.0385%
AVE	0.3250%	-0.3592%	0.1259%	-0.0601%	-0.3546%	0.4751%	-0.0557%	0.2762%

Alternate 4 with an elevated longitudinal profile and uniform cross slope of 1.1% for the first 10m (each side of centerline) was selected as the option that best fit the design criteria guidelines for transverse and longitudinal slope requirements. However, since the selected alternate requires a slope transition within the first 900m of the runway and requires 5m transition panels along the east and west sides of the centerline to tie back into the existing pavements it is necessary to perform additional analysis to insure that the transitional areas will not have an adverse affect on aircraft performance. Currently, there are no criteria or guidelines established for military or civilian aircraft to quantify the roughness affect of pavements on aircraft performance. The closest criteria to mitigate for surface roughness would be the construction specification tolerance requirements for the construction of new pavements for smoothness (no abrupt changes in excess of ¼-inch, straight edge or profilograph testing, and plan grade conformance tests) which normally will result in pavements with acceptable ride quality (even these tests however may not account for resonance affects to aircraft performance induced by multiple high-low areas). Construction tolerance tests are applicable to new pavements and do not quantify the affects to aircraft on warped or transitional panel sections which have multiple and varying elevations. Therefore, in order to properly access and quantify the affects of the proposed pavement transitional panels and the slope transition in the 1st 900m of the runway a ride quality analysis needed to be preformed for the forecasted aircraft mix.

AIRCRAFT RESPONSE ANALYSIS

APR Consultants were given design data that reflected the constraints required to tie keel section replacement into the existing pavement, both longitudinally and transversely. Elevation data of the proposed pavement alternate was calculated by KBR in 1 foot increments. The Excel data was converted into longitudinal profile data compatible with APR Consultants aircraft simulation software. Takeoff and landing simulations were conducted in both runway directions for a variety of aircraft. These included the F-16, the F-18, a Boeing 737-800 and a Boeing 747-400. This mix of aircraft provided an adequate range of gross weight and landing gear configuration spacing to detect any wavelength of roughness that may cause unacceptable aircraft response.

Figure 1 is representative of the results produced in the analysis conducted. This figure shows an F-18 taking off on runway 32. The profile selected was one with varying transverse cross-slopes that produced an undulating longitudinal profile. The results show mild aircraft response. The top trace is the vertical acceleration at the pilot's seat. The middle trace is the vertical acceleration at the aircraft's center of gravity (cg). Both are banded by the criteria (+/-.4g). This criterion defines "the threshold of discomfort" as published in Volume III of the Shock and Vibration Handbook [1]. Additionally, this level of unwanted aircraft response is a threshold at which aircraft fatigue damage begins to occur with dynamic loading. This .4g level has become accepted by many in the industry as a standard for when an airport pavement is in the rough category. This is not a hard and fast rule, but is an indicator that if exceeded, it would be advisable to examine that section of pavement in more detail. The bottom trace is a plot of the runway profile as it is encountered by the main landing gear.

Figure 2 shows the results of a Boeing 747-400 taking off on that same profile. The results show a very benign aircraft response.

The profile used in these simulations is the farthest (50 feet) from the runway centerline and as a result had the most longitudinal undulations of all profiles analyzed. In normal aircraft operations it is very unlikely that theses surfaces will be encountered during takeoff. The most likely exception would be a formation takeoff of several fighters side by side. To fully evaluate this profile however, all of the aircraft listed above were simulated taking off on this profile.

Landings simulations were also conducted on this off CL profile. The results were also mild. The main landing gear track for both the Boeing 747 and the KC-10 for example, is less than 40 feet. So that would require a drift of 29 feet off of the CL. This is possible, but not likely to occur very often. The most likely time this outer profile would be encountered is during touchdown, with strong crosswind conditions.

It should be noted that when an aircraft is landing, the weight of the aircraft is mostly supported by the wings and the landing gear struts are fully extended. In general, the higher an aircraft is on the struts, the more roughness it can absorb. This fact will greatly minimize aircraft response. In addition, the aircraft is lighter during landing which also reduces aircraft response to pavement roughness. Also, if drift did occur the pilot would correct as soon as possible once he has directional control with the nose landing gear steering, rudder and differential braking. So he wouldn't remain on this track for long.

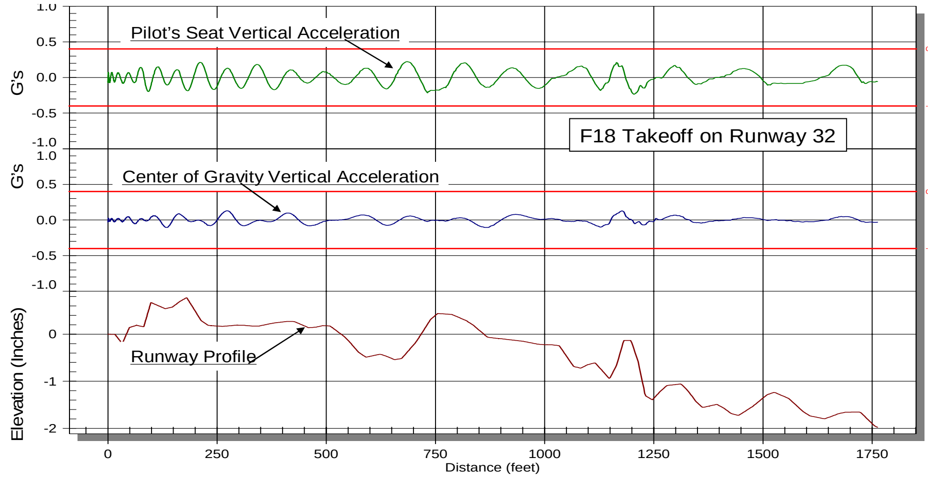

Figure 1. Simulated Takeoff of F-18 on Runway 32.

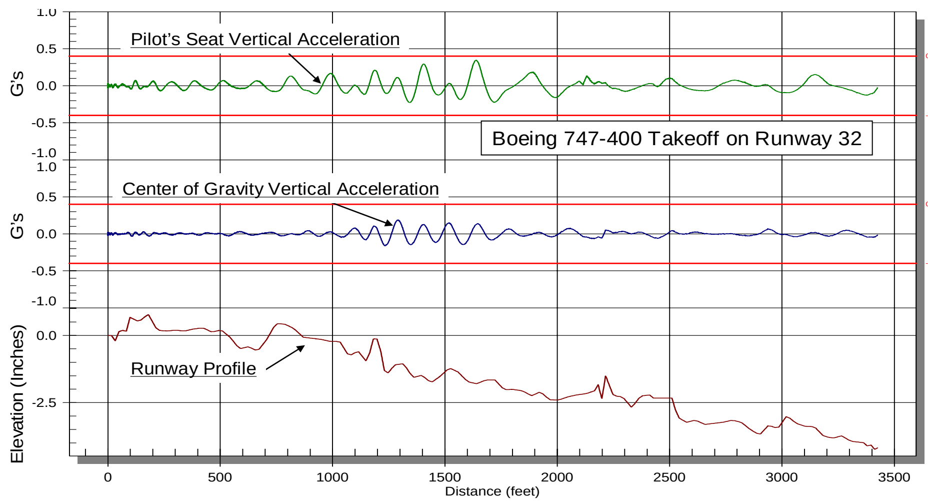

Figure 2. Simulated Takeoff of Boeing 747-400 on Runway 32.

Figure 3 shows the deviation from a simulated 100-foot straightedge at the transition areas before and after the keel section. The 100-foot straightedge is a tool developed by APR Consultants and is use primarily to expose long wavelength roughness events. APR's experience using the 100-foot straightedge is that anything less than 1-inch will not adversely affect the aircraft's ride quality unless there are repeated bumps and dips

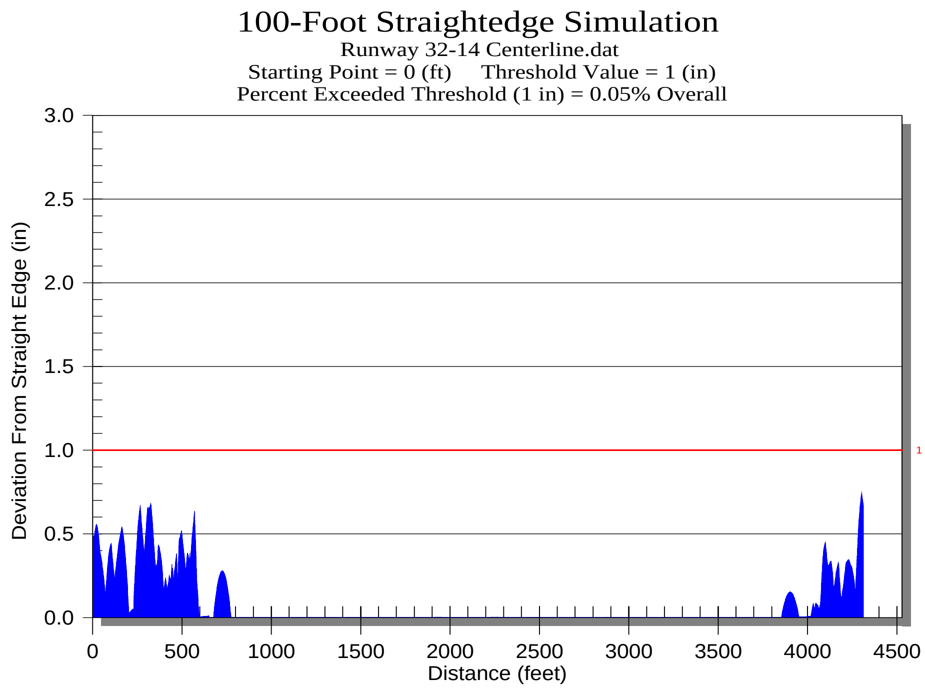

Figure 3. 100-Foot Straightedge Assessment of Runway 14-32.

CONCLUSIONS

The design of the keel section replacement of runway 14-32 required that the new pavement tie into existing pavement while minimizing surface roughness. Through an initial analysis of multiple gradient longitudinal and transverse slope scenarios the recommended option was to raise the centerline profile, maximize the transverse uniform cross slope, optimize the transverse slope differentials, and minimize the transverse transitional panel section distance. The transverse tie-ins were the challenge because of the continuously varying cross slopes. These translated into longitudinal undulations that could have imposed unwanted aircraft response. It was uncertain at the time how these undulations would affect aircraft ride quality. Since it is much more cost effective to make corrections (if needed) to a design than it is to concrete already placed, it was decided to evaluate the design with aircraft simulation.

The simulation results of multiple aircraft types provided quantitative engineering data to validate that the design was, in fact, acceptable with all simulations producing very mild aircraft responses (aircraft responses less than 0.4g) and provided assurance that the KBR design produced acceptable aircraft ride quality. The design and analysis was approved by the client, the pavement was successfully constructed as designed, and is in use with favorable responses from pilots as to runway surface ride quality.

REFERENCES

1. Volume III of the Shock and Vibration Handbook, Chapter 44 “Effects of Shock and Vibration on Man” by D. E. Goldman and H. E Von Gierke.