Comparisons of GNSS and Leveling-derived Orthometric Heights Using Geographic Information System Software (G13A-0940)

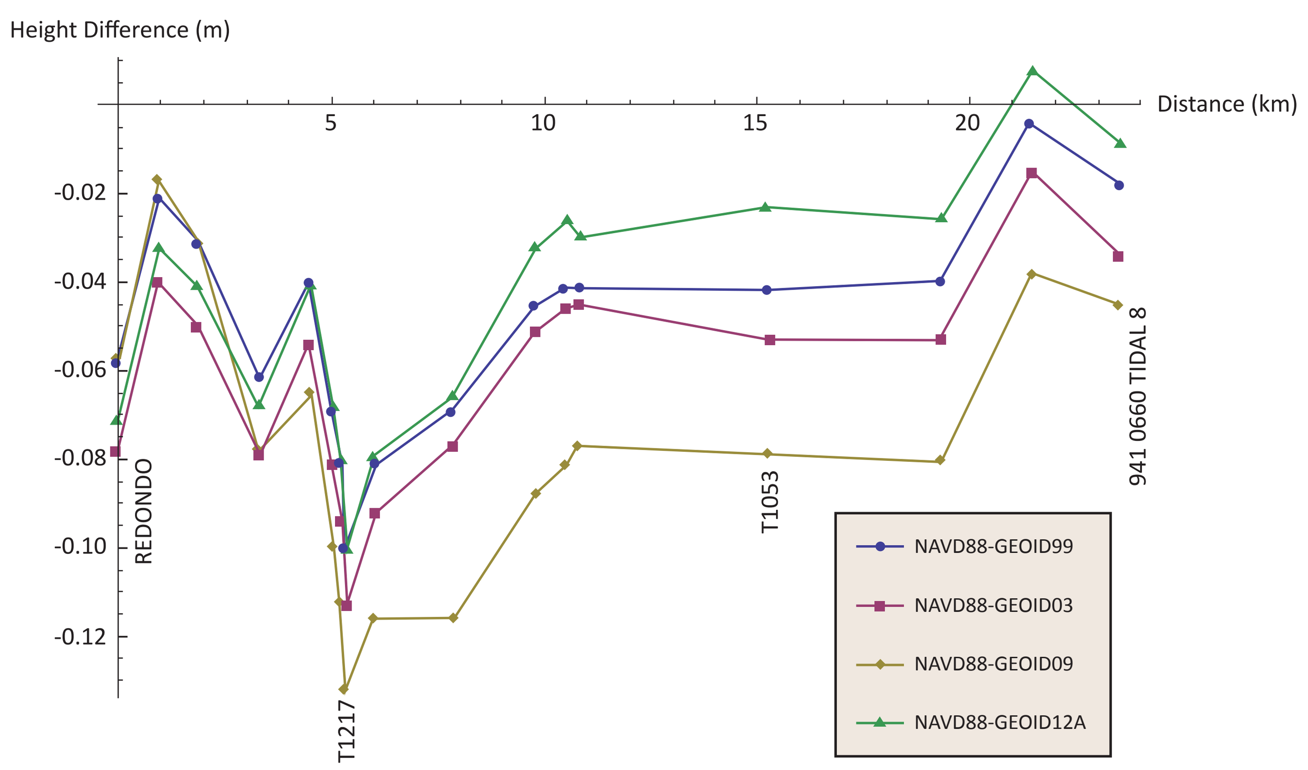
• Kevin M. Kelly, M.A.Sc, OLS - Esri, Redlands, California kevin_kelly@esri.com • Jay Satalich, PLS - State of California, Department of Transportation, District 7 jay_satalich@dot.ca.gov

Introduction

National Geodetic Survey (NGS) has produced no less than six gravimetric and hybrid geoid models for the conterminous U.S. since the early 1990's, the most recent being GEOID12A. The ability of the hybrid geoids to reproduce NAVD88 orthometric heights has steadily improved with each new model. However, in the Palos Verdes Peninsula of Southern California,discrepancies of up to -8 cm persist between published NAVD88 heights and those derived from GNSS on benchmarks using the last four geoid models: GEOID99, GEOID03, GEOID09 and GEOID12A. We examine some potential causes for these discrepancies.

Geoid Differences

The plot and tables below show differences between NAVD88 and GNSS-derived orthometric heights along a northwest running 23 km long leveling line in the Palos Verdes peninsula using four NGS geoid models: GEOID99, GEOID03, GEOID09 and GEOID12A. Differences at REDONDO are due to monument disturbance by local construction. Benchmarks T1217 and T1053 exhibit differences of over 4 cm in orthometric height during the period 1960 through 1994. However, the ellipsoid height at T 1217 is stable at the 1 cm level between 1997 and 2012. We see steady improvement from GEOID99 to GEOID12A; however, differences still reach -8 cm even with GEOID12A. We also see that each hybrid geoid model surface lies consistently above the surface defined by NAVD88 in this region.



	N	Min	Max	Mean	Std Dev
NAVD88-GEOID12A	17	-0.099	0.008	-0.046	0.029
NAVD88-GEOID09	17	-0.132	-0.017	-0.077	0.032
NAVD88-GEOID03	17	-0.113	-0.015	-0.062	0.025
NAVD88-GEOID99	17	-0.100	-0.004	-0.050	0.025

Table 1. Statistics of the differences between NAVD88 and GNSS-derived orthometric heights in meters. Benchmarks T1217 and T1052 included.

	N	Min	Max	Mean	Std Dev
NAVD88-GEOID12A	15	-0.080	0.008	-0.044	0.027
NAVD88-GEOID09	15	-0.116	-0.017	-0.073	0.031
NAVD88-GEOID03	15	-0.094	-0.015	-0.059	0.023
NAVD88-GEOID99	15	-0.081	-0.004	-0.047	0.023

Table 2. Statistics of the differences between NAVD88 and GNSS-derived orthometric heights in meters. Benchmarks T1217 and T1052 excluded.

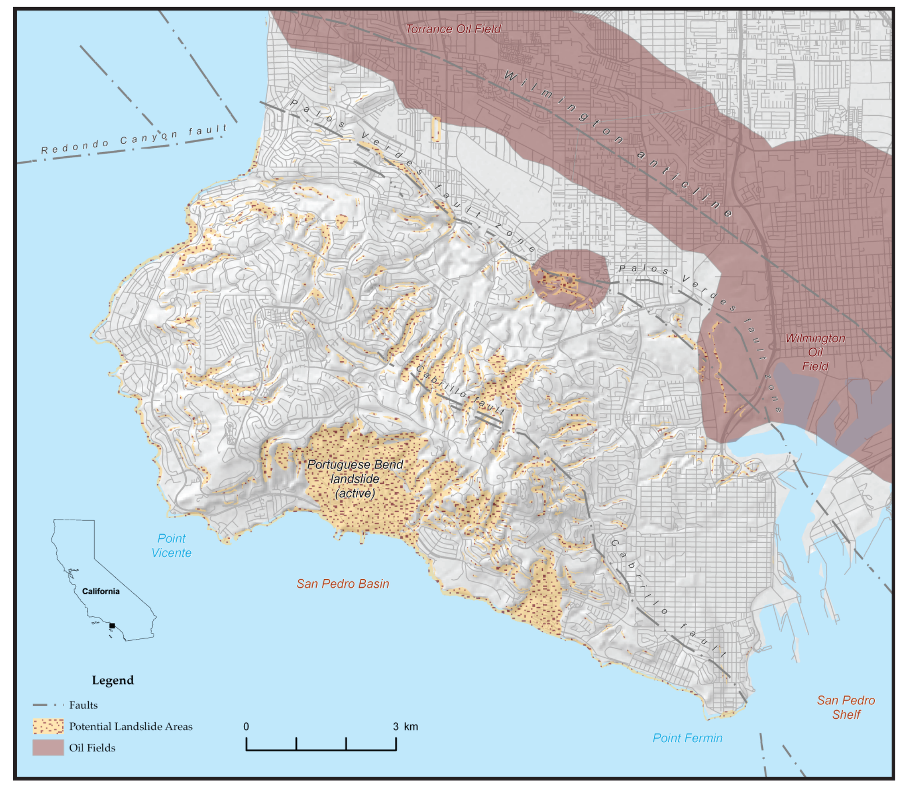


FIGURE 1. Key geophysical features influencing benchmark heights near the Palos Verdes Penninsula, California.

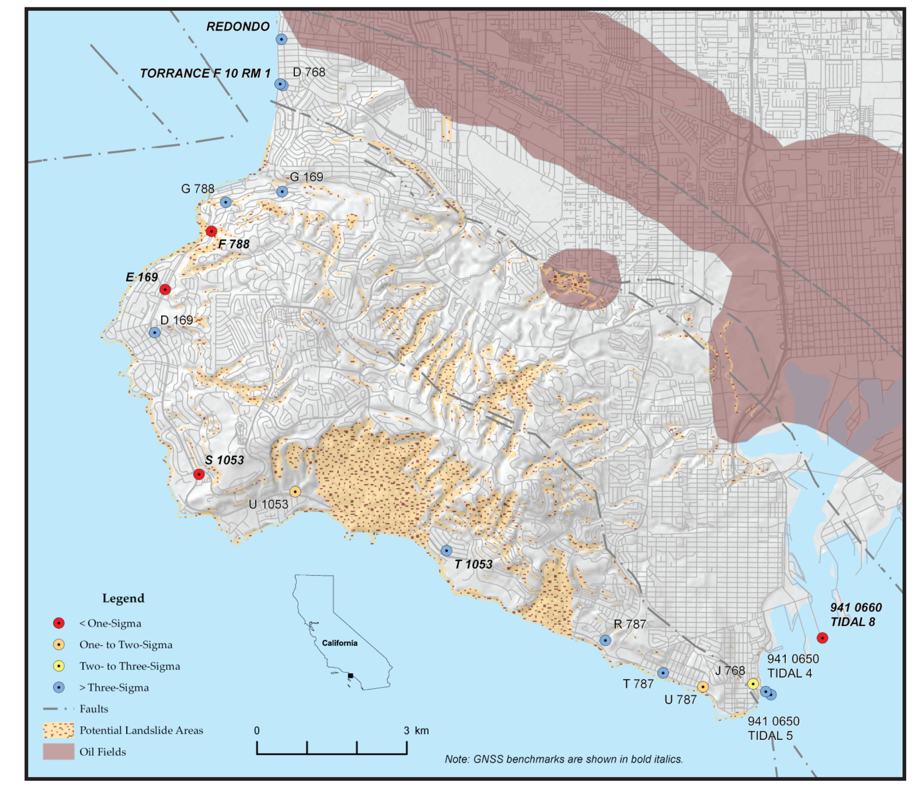


FIGURE 2. New-minus-old comparison of geodetic leveling shown as a component of error propagation. L25468/14 (1994) minus L17850 (1960)

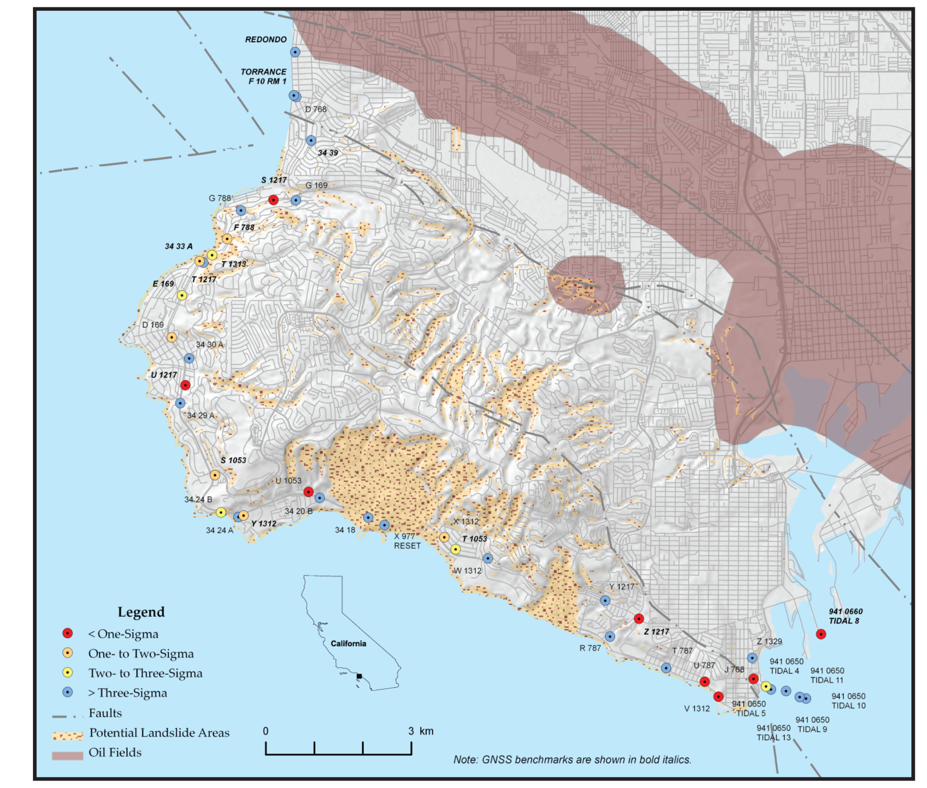


FIGURE 3. New-minus-old comparison of geodetic leveling shown as a component of error propagation. L25468/14 (1994) minus L24301/1 (1978)

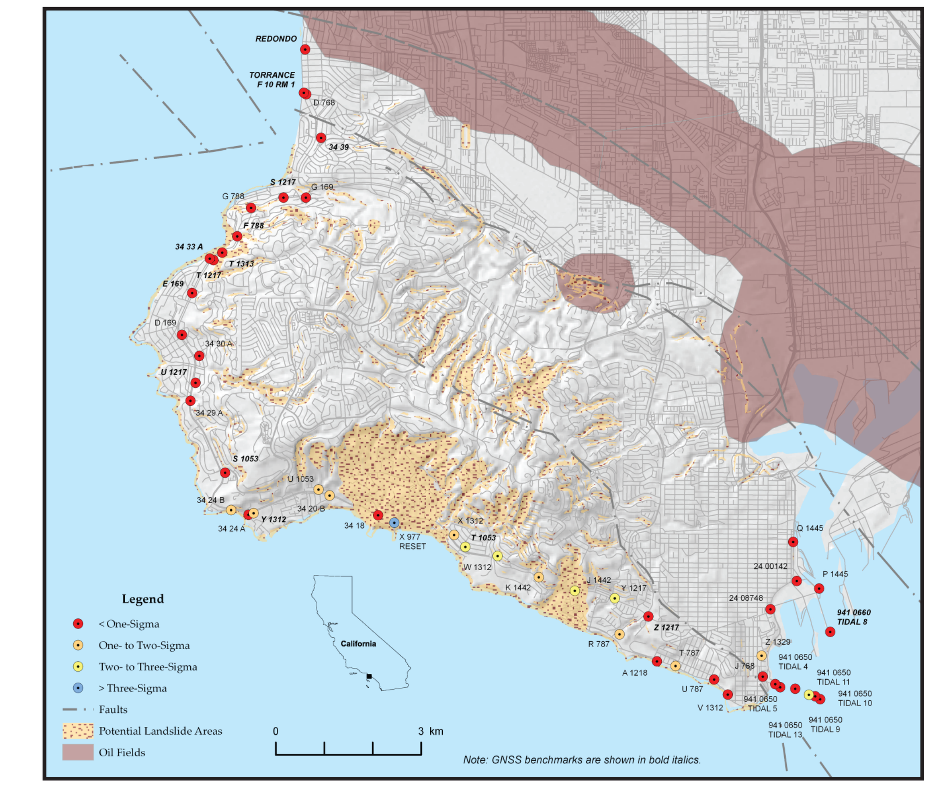


FIGURE 4. New-minus-old comparison of geodetic leveling shown as a component of error propagation. L25468/14 (1994) minus L25180 (1989)

Geodetic Leveling Analysis

The National Geodetic Survey (NGS) generously provided geodetic leveling observations used in this study and those observations date from the 1994, 1989, 1978, and 1960 epochs. The following corrections are applied to the leveling observations: orthometric, rod, level, temperature, astronomic, refraction, and magnetic. All levelings were performed to first-order specifications as they existed at the time of the observations.

New-minus-old comparisons of the geodetic leveling are performed at benchmarks common between the two epochs and use the 1994 leveling as the basis for all comparisons. One first-order leveling line observed in 1971 (L22292) was analyzed initially but was not used because our analysis indicates that L22292 may be contaminated with some type of systematic error - perhaps magnetic. All new-minus-old comparisons are relative to 941 0660 TIDAL 8 (DY1083) which is selected as an arbitrary starting benchmark.

New-minus-old Leveling Comparisons

Analysis of the geodetic leveling over time indicates regional trends. One of the more dominant sources of movement along this leveling line lies north of the Palos Verdes fault zone and is consistent with subsidence due to oil extraction in the Torrance/Wilmington oil field. The maximum settlement in this area is -19 cm at benchmark REDONDO between the 1994 and 1960 epochs; however, the subsidence appears to stop after 1978 when large-scale oil pumping in the western portion of the Torrance oil field ceased. In the context of this study, we suspect that subsidence due to oil extraction influences the heights at benchmarks TORRANCE F 10 RM 1 (DY1217) and REDONDO (DY1212), and perhaps 34 39 (DY9095) but only prior to 1989.

Another notable movement area is the Portuguese Bend landslide zone located on the southern part of the Palos Verdes Peninsula. Comparing geodetic leveling between the 1994 and 1978 epochs, benchmarks X 977 RESET (DY1004) and 34 18 (DY9026) indicate over -0.9 m of settlement in the landslide area. The GNSS portion of this study carefully avoids using any benchmarks located in the Portuguese Bend landslide area where movement is both well-known and on-going.

Based upon the geodetic leveling comparisons, the southernmost portion of the Palos Verdes Peninsula appears to be least stable. Besides the Portuguese Bend landslide, another ancient landslide zone exists about 5 km northwest of Point Fermin. Conversely, the most stable portions of the Palos Verdes Peninsula lie near Point Vicente and Point Fermin, which are both located near outcrops of basalt. Comparing differences between the 1994 and 1989 leveling epochs, benchmarks located in the western portion of the Palos Verdes Peninsula appear to be stable relative to 941 0660 TIDAL 8.

Estimates Of Error Propagation

This study uses *a posteriori* error estimates from double-run leveling sections to estimate precision. All geodetic leveling observations prior to 1989 were double-run. Leveling from the 1989 and 1994 epochs used single-run observations that achieved first-order section checks with past leveling observations. Error propagation estimates for all leveling observations were calculated using the error of the sum statistic for a 1-km section of double-run leveling between the two respective leveling epochs: $\sigma_{New-Old} = \sqrt{\sigma^2_{New} + \sigma^2_{Old}}$, where σ is the *a posteriori* standard error for 1-km of double run leveling. Benchmarks shown in red on the maps shown here indicate that any apparent difference in height between the two levelings is within the noise of the combined set of observations and benchmarks shown in blue indicate movement greater than three standard deviations.

BENCHMARK	PID	RUNNING DISTANCE (km)	1994 minus 1989	1994 minus 1978	1994 minus 1960
941 0660 TIDAL 8	DY1083	0.00	FIXED	FIXED	FIXED
Z 1217	DY1118	8.95	0.00358	0.00138	none
T 1053	DY0994	13.30	0.01375	0.00814	0.04157
Y 1312	DY2499	18.38	0.00912	0.00541	none
S 1053	DY1017	19.89	0.00432	0.00495	0.00038
U 1217	DY1227	21.94	0.00208	-0.00321	none
E 169	DY1230	23.97	0.00421	-0.01158	0.00857
T 1217	DY1231	24.66	-0.00595	-0.02714	none
34 33 A	DY9050	24.77	0.00115	-0.00636	none
T 1313	DY2498	24.97	0.00330	-0.01071	none
F 788	DY1233	25.54	-0.00270	-0.00917	-0.00741
S 1217	DY1237	27.01	0.00368	-0.00131	none
34 39	DY9045	29.08	-0.00103	-0.01846	none
TORRANCE F 10 RM 1	DY1217	30.12	-0.00447	-0.03458	-0.05578
REDONDO	DY1212	31.04	-0.00178	-0.11205	-0.19149

Table 3. New-minus-old comparison of orthometric heights in meters.

GNSS STATION	2012 minus 2011	2012 minus 1997	2012 minus 1994	2012 minus 1992
PALOS VERDES ARIES 7268	FIXED	FIXED	FIXED	FIXED
941 0660 TIDAL 8	0.007	none	0.014	0.012
Y 1312	none	none	-0.003	none
S 1053	none	0.000	none	none
U 1217	none	0.004	none	none
T 1217	none	0.010	none	none
T 1313	none	0.004	0.008	none
F 788	none	-0.006	none	none
34 39	none	0.009	none	none
TORRANCE F 10 RM 1	none	-0.002	0.003	none
REDONDO	none	0.036	none	none

Table 4. New-minus-old comparison of ellipsoidal heights in meters.

NGS ACCESSION NUMBER	NAME	A POSTERIORI STANDARD ERROR (mm)	YEAR
L25468/14	SANTA MONICA VIA REDONDO BEACH TO SAN PEDRO	±1.17	1994
L25180	VENTURA VIA SANTA MONICA TO SAN PEDRO CA	±0.99	1989
L24301/1	AVILA BEACH VIA SANTA BARBARA NEWPORT BEACH TO SAN DIEGO	±0.93	1978
L17850	SAN PEDRO TO OXNARD CALIF	±2.31	1960

Table 5. Geodetic leveling lines used during this study. *A posteriori* error statistics are shown for 1-km of single-run leveling.

Conclusions

In the Palos Verdes Peninsula of southern California, discrepancies of up to -8 cm persist between published NAVD88 heights and those derived from GNSS on benchmarks using the last four geoid models: GEOID99, GEOID03, GEOID09 and GEOID12A.

Differences in geoid undulation between GEOID12A and GEOID09 cannot be attributed to differences in the geocentricity of the NAD83 reference frame since ellipsoidal heights in the Palos Verdes region differ by not more than 3 cm between NAD83(NSRS2007) used to generate GEOID09 and NAD83(2011) 2010.00 used for GEOID12A.

Analysis of differential leveling over four epochs spanning 34 years reveals that benchmarks are stable, thus eliminating mark movement as a cause for observed geoid differences.

Please contact kevin_kelly@esri.com or jay_satalich@dot.ca.gov
More information on GIS can be found at esri.com