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**Ground-motion variability resulting from the January 17, 1994,
 $M = 6.6$ Northridge Earthquake at the interchange between
highways 14 and I-5 in the northern San Fernando Valley**

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4 February 1994

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Abstract

Lawrence Livermore National Laboratory responded to the 17 January, 1994, $M = 6.6$ Northridge earthquake by sending an information gathering team to observe and study the collapse of the interchange between highways 14 and I-5 in the northern San Fernando Valley. This field team examined the structural failure at the interchange and the surface soil conditions, and they installed high-gain RefTek seismic recorders to record aftershocks. We recorded aftershocks for two weeks. Analyses of aftershock recordings in this report illustrate the degree of differential support motion for this site, and the higher than expected ground motion from an earthquake of this size and distance.

We analyzed records of small earthquakes ($M < 3.0$) at three locations separated by 260 to 800 m. The aftershock recordings reveal a substantial relative spectral amplification of a factor of 2 to 8 in the 1 to 15 Hz range across the interchange area. Also, substantial secondary arrivals are generated at two locations in the area. The entire interchange area is situated on interbedded sandstone of varying consistencies, and is surrounded by ridges of the San Gabriel mountains. Since the surface geology is all sandstone, we attribute these effects to subsurface geologic variations and topographic variations.

We used the aftershock recordings of small earthquakes as empirical Green's functions and synthesized strong ground motion at three sites in the interchange area. Results presented here are based on an assumption that the geology of the interchange area remained linear in its response to the main event. From our synthesized ground motions, we estimate 1) peak acceleration to have been near 1 g due to the topographic and geologic conditions, and the geometry of the fault rupture; 2) differential displacement across the north and south extremes of the area to be about 40 to 60 cm, owing to wave passage effects and local geologic and topographic conditions; and 3) relative motion to be fairly coherent up to only about 1 Hz, and highly incoherent above about 5 Hz.

Introduction

Lawrence Livermore National Laboratory responded to the 17 January, 1994, $M = 6.6$ Northridge earthquake by sending an information gathering team to observe and study the collapse of the interchange between highways 14 and I-5 in the northern San Fernando Valley. This field team examined the structural failure at the interchange and the surface soil conditions, and they installed high-gain RefTek seismic recorders to record aftershocks. Plate 1 shows the damage to the interchange.

We recorded aftershocks for two weeks. Analyses of aftershock recordings and synthesis of the main event illustrate the degree of differential ground displacements and the higher than expected ground accelerations that may have occurred from the main event. We analyzed records of small earthquakes ($M < 3.0$) at three locations separated by 260 to 800 m. We also exercised the LLNL methodology for predicting the linear-response strong ground motion that may have occurred at the interchange from the main event. Our method uses recordings of small earthquakes as empirical Green's functions to constrain the actual geological and propagation path information, and utilizes a rupture model constrained by the hypocenter, rupture geometry, and moment of the main event. We calculated ground motion at three sites along the interchange: the south and north abutments of the southbound connector of Hwy 14 to I-5, and a central location to the interchange. Figure 1 shows these site locations and the interchange (one week after the earthquake). Results presented here are preliminary. In particular, results are based on an assumption that the geology of the interchange area remained linear in its response to the main event.

Geology

The Northridge earthquake occurred in a geologically complex region of the Transverse Ranges of California in the San Fernando Valley. The Transverse Ranges are a geologic province of westward-trending ranges and valley, characterized by complicated structural and topographic relief. These features result from an active tectonic north-south compression associated with right lateral movement along the northwestward-trending San Andreas fault system. This compression has resulted in a complex distribution of east-west trending thrust faults beneath the San Fernando Valley, and along the frontal fault system of the Santa Susanna mountains. Figure 2 shows major faults and recent earthquakes in the region.

Figure 3 shows the geology of the San Fernando Valley area, and the locations and rupture areas of the 1971 San Fernando earthquake and the 1994 Northridge earthquake. Rupture areas

are estimated here from locations of aftershocks. The geology of the San Fernando valley includes alluvial deposits that extend to a depth of at least 150 m, and sedimentary material that fills the valley to a thickness of at least 3.6 km and possibly 6.1 km (Morton and Baird, 1975; Duke *et. al.*, 1971). Figure 4 shows the geology surrounding the interchange area and location of instruments. Surface expression of sandstone extends to at least a 1.5 km radius from the highways 14 and I-5 interchange. Gneiss is the closest rock outcrop, at site IGN. Site observations of the interchange indicate that the surface geology is composed of interbedded sandstone of varying consistency from poorly consolidated to near crystalline composition, and varying in thickness from of a few inches to 20 to 30 ft. Examination of the railroad tunnel entrance beneath the interchange reveals that the sandstone formation extends to at least 20 feet below ground level of the interchange pillars.

Instrumentation

Immediately following the earthquake LLNL seismologists initiated a field deployment of weak- and strong-motion seismic recorders. The weak motion recorders consisted of 16-bit fixed-gain instruments with 1 Hz free-period, high-gain Teledyne Geotech S-13 seismometers. The effective recording bandwidth (flat to velocity) was 0.2 to 100 Hz. The digital seismograms have been instrumented to be proportional to velocity in nm/sec over the frequency ranges recorded. The individual seismometer constants (free-period, damping, and seismometer gain) were determined from step calibration pulses, and are correct to within 5%. Table 1 lists the station locations, geology, and period of operation. Table 1 also lists the station i.d.'s used in this report, and the data file i.d. (in parentheses) used for computer files.

Site Specific Site Response

Comparison of small earthquake ($M < 3.0$) recordings across the interchange are used to examine the site geologic response. Figures 1 and 4 show the location of recording sites IRK, ICN, and ICB, which form a rough north-south line along the axis of the interchange. Figure 5 shows seismograms at the three sites from a magnitude 2.7 earthquake with hypocentral distance of 5 km, and Figure 6 shows seismograms at the three sites from a magnitude 2.1 earthquake with hypocentral distance of 10 km. These events are effectively point sources, and the seismic energy has traveled along the same path from the earthquake to the interchange. The differences in the

recordings is due to differences in geology and topography at the recording sites. It is apparent that there is considerable amplification in the site response at sites ICN and ICB as compared to site IRK. Also, it is apparent that large (relatively) secondary arrivals are being developed at the ICN and ICB as compared to site IRK.

Figures 7 and 8 shows the spectral ratio for the same events as shown in Figures 5 and 6, following the procedures outlined by Jarpe *et. al.*, 1989. Figure 7 shows that the amplification between sites ICB and IRK is about a factor of 4 in the 4 to 10 Hz range, and a factor of about 2 in the 1 to 4 Hz range. Figure 8 shows that amplification between sites ICN and IRK is about a factor of 5 in the 4 to 10 Hz range, and about a factor of less than 2 in the 1 to 4 Hz range.

Recording Site Variation

An important question to ask is "If important variations in amplification and waveforms occur over such short distances, maybe they are also important over even shorter distances, maybe it matters a lot where one places the sensors?". To test this we set up an experiment whereby we recorded events at site IRK and another site 50m east on the abutment to the Hwy 14 connector, and at site ICN and another site 100 m west, farther into the ravine. The abutment is a very massive concrete structure and is imbedded in the sandstone, although not the same strata as IRK. The alternate site to ICN is also in the center area, but on the other side of a small gully. Both alternate sites are shown in Figure 1 as small white rectangles without i.d. initials. Figure 9 shows a single component of a recording at IRK and the alternate site. The similarity of waveforms is obvious. It is interesting that the maximum peak is different by almost a factor of two between the two sites. The waveforms between the ICN site and the alternate site were different, but the character was the same and the spectral amplifications relative to IRK were essentially the same. The answer to the question appears to be that variations in this area are significant over short distances (200 to 800 m), but not over very short distances (50 to 100 m). This is not a conclusive study but only a preliminary examination of the problem.

Synthesized Ground Motion

Using the recordings of small earthquakes as empirical Green's functions, we synthesized the ground motion from the main earthquake that many have occurred at the interchange. We followed the approach of Hutchings and Wu (1989) who use empirical Green's functions for explicit solutions to the representation relation (Aki and Richards, 1980). The source events for the empir-

ical Greens's functions should be small enough that they occur as effectively impulsive point dislocation sources. Generally events less than magnitude $M = 2.5$ satisfy this criterion. The rupture model is derived from preliminary reports of aftershock locations. Figure 3 shows the epicenter of the event as described by California Institute of Technology (personal communication), and an area that roughly defines the interior of the aftershock zone. A smaller area than the actual aftershock zone is used since previous experience has shown that aftershock zones tend to extend beyond the actual rupture area of the main event. The moment is 1.5×10^{26} dyne-cm. This was chosen to be equal to the average value determined by several studies for the 1971 San Fernando earthquake (Hutchings, 1994), since the magnitude of the Northridge earthquake is comparable to that of the 1971 San Fernando earthquake. Figure 10 shows the slip distribution for the rupture model. A Kostrov rupture model with healing as described by Hutchings (1991) was used. The rupture and healing velocities were 0.9 times and 0.8 times the shear wave velocity, respectively. Figure 11 shows the source pulse that would occurred at the Interchange from this source. It is noteworthy to point out that this moderately complicated source pulse is a result of a simple source model that does not have irregularities in rupture velocity, stress drop, or slip rate. This effect is discussed in Hutchings (1994). Figures 12, 13, and 14 show the synthesized acceleration, velocity, and displacement at the three sites for this source model. The highly complex ground motions computed is a result of the complexities in the geology between the earthquake and the recording site. Peak accelerations range from 1.1 to 1.3 g across the valley. Also, note the high frequencies that occur at sites ICN and ICB that are not apparent at site IRK. Both of these effects are entirely due to differences in site geologic response.

Estimated Differential Ground Motion

The relative ground motion between the three sites along the Interchange can be computed from the synthesized seismograms. Figure 15 shows the relative displacement in three directions between site pairs. Sites IRK and ICB are at the two extremes of the Interchange and show a relative displacement of 40 cm in the north-south direction and 60 cm in the east-west direction. The north-south direction is longitudinal to the Hwy 14 connector that separated along expansion joints. Site ICN is in the central area of the Interchange, and differential displacements of 20 cm in the north-south direction and 10 cm in the east-west direction were calculated. These represent strains of about 10^{-3} across the Interchange. Figure 16 shows the coherence of the acceleration,

velocity, and displacement as a function of frequency. Here, synthesized seismograms that used the same source events as Green's functions were used to limit variability resulting from different source events. Seismic energy remained fairly coherent up to only about 1 Hz, and highly incoherent above about 5 Hz across the valley.

Conclusions

We analyzed records of small earthquakes ($M < 3.0$) at three locations separated by 260 to 800 m. The aftershock recordings reveal a substantial relative spectral amplification of a factor of 2 to 8 in the 1 to 15 Hz range across the interchange area. Also, substantial secondary arrivals are generated at two locations in the area. The entire interchange area is situated on interbedded sandstone of varying consistencies, and is surrounded by ridges of the San Gabriel mountains. Since the surface geology is all sandstone, we attribute these effects to subsurface geologic variations and topographic variations.

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Acknowledgements

We would like to thank the many Caltrans individuals that allowed access to the interchange at a difficult time.

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Table 1: Aftershock Recording Sites

No., Ident.	Operation	Latitude elevation	Longitude/ instrument component	Geology	Description
ICN (I5_14)	2105 22 Jan 1931 03 Feb	34.3351 450 m	118.5072 u. n. e.	moderately con- solidated sand- stone	Center of interchange
IRN (I5_SR)	0044 20 Jan 1800 21 Jan	34.336 450 m	118.516 u. n. e.	Poorly consoli- dated sandstone	300 m west of interchange
IGN (MW_23B)	0429 02 Feb 1555 02 Feb	34.3381 670 m	118.4862 u. n. e.	Gneiss, compe- tent	Tunnel hill, 2 km east
ICB (I14_CB)	2349 20 Jan 2222 21 Jan	34.3401 450 m	118.5070 u. n. e.	moderately con- solidated sand- stone	150 m north of north abutment.
IRK (14_15)	0429 02 Feb 1624 03 Feb	34.3329 450 m	118.5083 u. s. w.	Very hard sand- stone	30 m south of south abutment

Plate 1. Damage to the Hwy 14
and I-5 Interchange.

Douglas C. Pzac

Figure 1. Solid circles are sites of study, open squares are alternate sites.

Figure 2. A major faults and recent earthquakes in the region.

Figure 3. The geology of the San Fernando Valley area, and the locations and rupture areas of the 1971 San Fernando earthquake and the 1994 Northridge earthquake (geology modified from Jennings, C. W. and R. G. Strand, 1969).

OLDER SURFICIAL SEDIMENTS

dissected, weakly consolidated alluvial deposits
Qoa older sandy alluvium, including slope wash, derived from Chatsworth
Qoa older alluvium composed largely of angular pebble-size fragments of
some of sandstone (Tm, Tn, and Tps) in light gray to tan silty matrix
calcareous calcareous, crudely bedded to massive; about 200 ft (60m) thick;
upslope in Browns Canyon drainage area into old debris-flow landslides (and
much dissected where elevated; but at Horse Flats top surface of dry
Pliocene age; mapped as slope wash, older alluvium, and Saugus Fm
by Barrows 1975; Evans and Miller 1978; and Saul 1979; probably in place
Formation of Calkhoff 1958; Barrows et al. 1975; and Dibblee 1991

LANDSLIDE DEBRIS

TOWSLEY FORMATION

marine clastic; early Pliocene age (Rupertian) and possibly latest Miocene ("DeMontian SE")
Tos light gray to tan coherent to semi-friable sandstone, medium grain
pebbly, bedded; includes minor micaceous siltstone; grades laterally into
Formation (Ts) in San Fernando Pass area
Toc gray micaceous silty claystone and siltstone; minor sandstone

PICO FORMATION

marine clastic; mostly Pliocene age
Tps south of Santa Susana fault: Pico sandstone included in Saugus Fm
Pico Formation by Butler 1977, Lant 1977, Yeats 1987; Pico and Saugus
and Miller 1979) mostly light gray to nearly white, soft friable sandstone;
abundant whole and fragmented bivalve shells west of Browns Canyon;
to lagoonal conditions; grades upward into terrestrial Saugus Formation;
Miocene formations
Tps conglomerate in lower Umeikin Canyon; gray massive conglomerate
and metavolcanic rocks in sandstone matrix; nonmarine (?), unconformable
(Tm), overlain by Saugus Formation
Tp and Tps north of Santa Susana fault: Pico Formation of Kew 1924,
1952, 1962; Tps mostly light gray semi-friable sandstone, locally pebbly
bivalve shell fragments; intertongues into Saugus Formation (Ts); Tp m
siltstone-claystone, bedded to massive, includes few thin sandstone layers

Figure 4. The geology surrounding the interchange area and location of instruments.

Figure 5. Seismograms at the three sites from a magnitude 2.7 earthquake with hypocentral distance of 5 km.

Figure 6. Seismograms at the three sites from a magnitude 2.1 earthquake with hypocentral distance of 10 km.

Figure 7. The spectral ratio for the same events as shown in Figure 5.

Figure 8. The spectral ratio for the same events as shown in Figure 6.

Figure 9. The east component of a recording at IRK (solid line) and the alternate site (dotted line), located on the abutment.

Figure 10 The slip distribution for the rupture model. A Kostrov rupture model with healing as described by Hutchings (1991) was used.

Figure 11 The source pulse that would occurred at the Interchange from this source.

Figures 12 The synthesized acceleration at the three sites for the source model shown in Figure 9.

Figures 13 The synthesized velocity at the three sites for the source model shown in Figure 9.

Figures 14 The synthesized displacement at the three sites for the source model shown in Figure 9.

Figure 15 The relative displacement in three directions between site pairs. Sites IRK and ICB are at the two extremes of the Interchange and show a relative displacement of 40 cm in the north-south direction and 60 cm in the east-west direction.

Figure 16 The coherence of the acceleration, velocity, and displacement as a function of frequency. Here synthesized seismograms that used the same source events as Green's functions were used to limit variability due to different source events.

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