The Importance of Hydrogeologic Characterization and Analysis to Avoid Off-site Impacts in Highway Construction

Daniel B. Stephens[1], Farag E. Botros[1], Stanley Helenschmidt[2], Bill Casadevall[1], Peter Quinlan[3], and Daniel Davis[1]

[1]Daniel B. Stephens & Associates, Inc., 6020 Academy Road NE, Suite 100, Albuquerque, NM 87109; PH 505-822-9400; FX 505-822-8877; email: dan.stephens@dbstephens.com

[2]Helenschmidt Geotechnical, Inc., 5245 Avenida Encinas, Suite B, Carlsbad, CA 92008; PH 760-579-0333; FX 760-579-0230; email: stan.hgi@sbcglobal.net

[3]Dudek, 605 Third Street, Encinitas, CA 92024; PH 760-942-5147; FX 760-632-0164; email: pquinlan@dudek.com

ABSTRACT

Shortly after construction of a major freeway expansion, groundwater rose to the surface at an adjacent industrial park in coastal Southern California. Construction included a mechanically stabilized earth wall for support of the freeway expansion. Soil cement mixing was used to stabilize soils at the toe of the wall where the wall transected small alluvium-filled canyons. Upgradient of the soil cement zones, stone columns were installed through alluvial soils to bedrock in order to mitigate liquefaction. Stone columns were covered with a gravel drainage blanket. No formal analysis of the hydrogeologic conditions was apparently conducted as part of the engineering design. However, three-dimensional groundwater flow modeling clearly illustrated why one might expect rising groundwater *downgradient* of the mechanically stabilized wall. This case study illustrates the importance of hydrogeologic characterization and analysis in engineering design to avoid off-site property damage caused by rising groundwater.

BACKGROUND

Problems associated with shallow groundwater in an industrial park west of the Interstate Highways 5 and 805 (I-5/I-805) junction in San Diego, California were first reported in 2006 when standing water was noted at a truck loading dock and damage occurred to floor coverings in an on-site day school. Approximately two years later, rising water was noted in a fire hydrant shut-off valve, and water was observed seeping from soil and pavement causing surface runoff in paved areas of the subject property. Saturated soil conditions at the ground surface also adversely affected on-site landscaping resulting in the death of several mature trees. Leak tests performed on city water lines failed to detect any significant leakage. Significant seepage as well as accumulation of salt deposits was noted along the toe of the adjacent reinforced earth retaining wall constructed adjacent to the subject property.

A total of 40 soil borings were drilled between 2008 and 2009, with 36 monitoring wells installed to monitor groundwater levels and identify potential causes of shallow groundwater conditions. The groundwater data collected indicated no local water source within the spatial limits of the subject property.

Officials initially suggested that the cause of the shallow groundwater conditions might be related to the construction of the recently completed I-5 expansion immediately east of the subject property. The original, adjacent portion of I- 5 was completed circa 1966; the major elements of the foundation for the recent highway expansion were completed in 2005, approximately one year before shallow groundwater conditions were first observed. Foundation elements for the 4000 foot (1,219 meter) long plantable geosynthetic reinforced (PGR) earth wall, which was constructed to support new southbound bypass lanes, consist of a soil-cement zone, stone columns, vertical drains, gravel blanket and gravel leveling pad.

The objective of the investigation was to determine whether or not, construction of the southbound I-5 bypass lanes and associated improvements had contributed to shallow groundwater conditions in the adjacent lowlands and industrial park down gradient of the PGR wall.

SITE DESCRIPTION

The subject property consists of a 14-acre (56,655 square meters) industrial park. The site is located in Sorrento Valley, bounded on the north side by Carmel Mountain Road, to the west by Sorrento Valley Road and to the east by the southbound lanes of I-5 (Figure 1). The site is located on the eastern flank of Los Peñasquitos Creek floodplain at elevations ranging from about 21 to 25 feet (6.4 to 7.6 meters) above mean sea level (msl). Finished grades at the site slope west, toward the creek. The interstate is elevated approximately 72 feet (21.9 meters) above the industrial park and is founded on fill placed on a west facing hillside that extends eastward from Los Peñasquitos Creek floodplain to an elevation of approximately 300 feet (91.4 meters) (msl) on which both commercial and residential developments have been constructed in recent years.

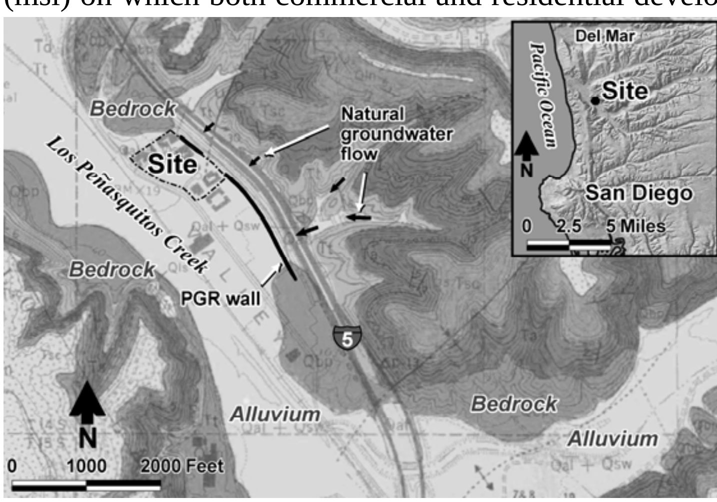


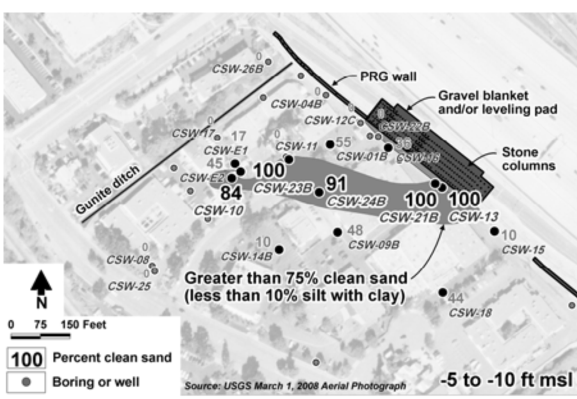
Figure 1 - Site Location and Geology

The portion of the subject property affected by the shallow groundwater was developed circa 1966. The affected area consists of 14 commercial buildings surrounded by asphalt driveways and parking areas with minor landscaped areas. Public utilities servicing the subject property include potable water, water supply for fire protection, storm water management, and wastewater (sewer).

GEOLOGY

Five geologic units occur within the study area, including Delmar Formation, Torrey Sandstone, and Ardath Shale of the Eocene La Jolla Group. Post-Eocene deposits include Bay Point Formation, alluvium, and artificially compacted fill (Figure 1). The Delmar Formation is typically sandy claystone interbedded with coarse-grained sandstone. The Torrey Sandstone is composed of medium- to coarse-grained, moderately well indurated arkosic sandstone. The Ardath Shale unit consists of a laminated siltstone that locally is gravelly or grades to silty sand, claystone, or sandstone. This unit dips generally east to southeast at 3 to 5 degrees. The Bay Point Formation is composed mostly of poorly consolidated, fine- and medium-grained, sand and/or sandstone. Holocene and older Quaternary alluvium consists primarily of poorly consolidated stream deposits of silt (often clayey), sand, and cobble-sized particles derived from bedrock sources that lie within or near the area (Kennedy and Peterson, 1975). Artificial fill consists of compacted earth materials derived from local sources and generally associated with construction of the freeway and office park development.

Two east-west trending, alluvium-filled canyons were covered by embankment fill during the construction of the freeway in 1966. The alluvium consists of very soft to soft silty clay interbedded with very loose to loose silty sand and sand in the south canyon area, and gravelly sand and clayey sand in the north canyon area. These alluvial deposits are underlain by intensely weathered residual Torrey sandstone or Delmar Formation that are very dense, and weakly to moderately cemented. Hydrogeologic investigations within the study area confirmed the presence of sand lenses that serve as permeable pathways (Figure 2).



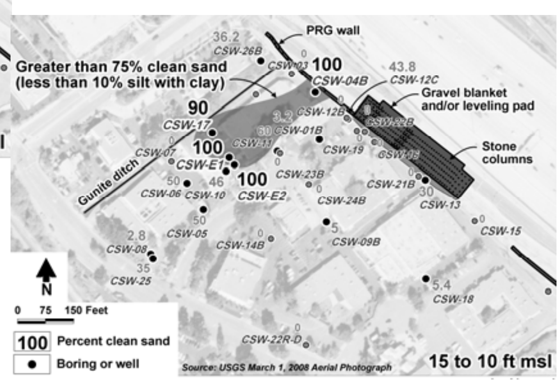
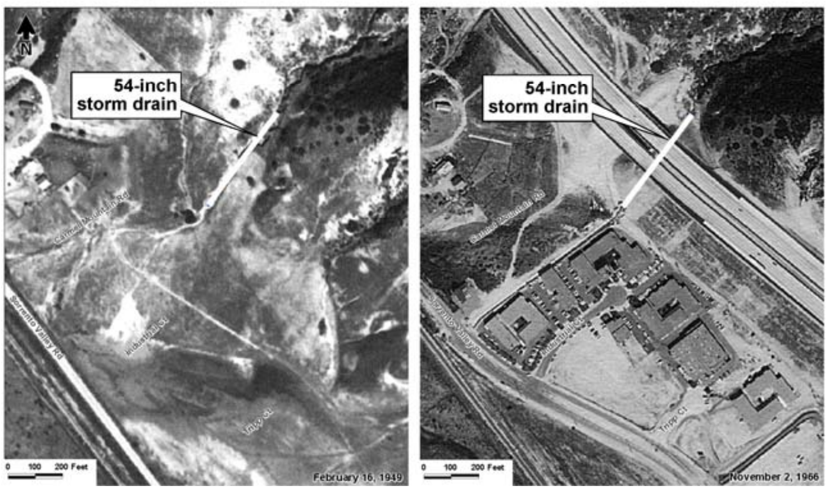


Figure 2 Permeable Sand Lenses within Alluvium

HYDROLOGY

Los Peñasquitos Creek flows northwest on the west side of the industrial park, toward the Pacific Ocean which lies approximately two miles west of the site. Prior to construction of the I-5 Freeway, surface water runoff was directed towards Los Peñasquitos Creek in southwest trending alluvial channels incised into the hillside east of the subject site. Following construction of the original I-5 (circa 1966), storm water runoff was collected east of the freeway and diverted via a series of culverts beneath the freeway to concrete lined brow ditches and/or storm drains which discharged into Los Peñasquitos Creek. One of these ditches is elevated several feet above existing grade in the industrial park and flows southwest across the north end of the site (Figure 3)

Figure 3. Storm Drain Pre- and Post-Construction of I-5

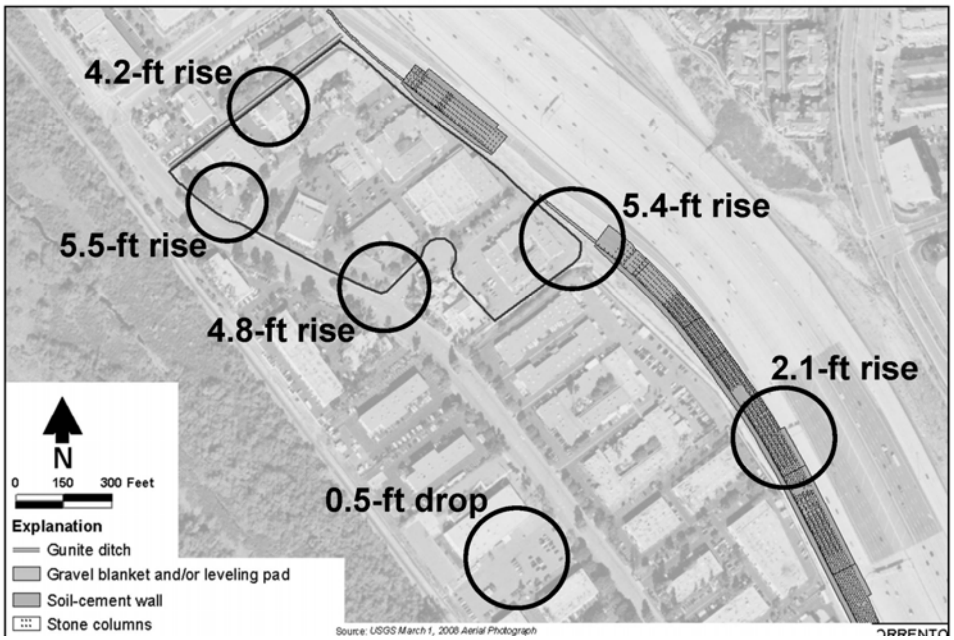


Groundwater beneath the industrial park occurs in the alluvial and bedrock units, and locally in artificial fill. However, in the subject area, the alluvial materials are much more permeable than the underlying claystone and sandstone bedrock and therefore transmit significantly more groundwater. Lenses of sandy alluvium extend westward from the historic surface water drainages into Los Peñasquitos Creek (Figure 2). East of the subject site, groundwater in the old alluvium-filled channels maybe perched or ephemeral. Groundwater also occurs in the bedrock formations to the east of the industrial park. But, the shallowest groundwater is likely perched on low permeability beds, especially near the higher portions of the developed hillside to the east.

Piezometers installed along the PGR wall, as well as other nearby monitoring wells, indicate that shallow groundwater generally flows westward in the bedrock and alluvial filled tributary channels extending beneath I-5. Groundwater passes beneath the industrial park and flows west towards Los Peñasquitos Creek and the Pacific Ocean. Because groundwater in bedrock discharges to the overlying alluvium in the floodplain, a vertical upward component of groundwater flow exists from bedrock to alluvium at the site.

Prior to completion of the freeway expansion, the depth to the water table beneath the industrial park was approximately five to nine feet (1.5 to 2.75 meters) below existing grades. During the period following construction through April 2010, the water table rose by approximately four to five feet (1.2 to 1.5 meters) over the subject site (Figure 4). Where the water table elevation exceeded existing site grades, seepage and surface flow occurred in landscaped areas as well as through asphalt and cracks in concrete flatwork. The area affected by seepage was approximately four acres (16,187 square meters). The groundwater discharge flowed along the street gutters, even during summer months, at a rate of up to approximately 10 gallons per minute (37.9 liters per minute).

Figure 4 - Post-Construction Groundwater Table Rise



HIGHWAY FOUNDATION AND DRAINAGE ENGINEERING

The PGR wall was constructed approximately 15 feet (4.6 meters) from the easterly edge of the site and varies in height from 23 to 72 feet (7.0 to 21.9 meters). Construction began in June of 2002 and continued through September of 2006, when paving of the new southbound on-ramp to the I-5 was completed.

The PGR mile long wall included special geotechnical recommendations and construction features to mitigate various geotechnical hazards along its length. The construction included installation of stone columns with a gravel blanket, wick drains (Prefabricated Vertical Drains), a gravel leveling course for the wall as well as gravel placed in excavation bottoms to allow for equipment mobility. A zone of soil cement mixing consisting of a 17-foot (5.2 meters) wide strip in front of the wall, was constructed between Stations 13+00 to 18+30, and 19+60 to 20+70 (stationing in meters south to north). The zones of soil cement were placed within alluvial channels and are effectively a pair of long strips 1,740 feet (530 meters) and 360 feet (110 meters) long, that extend approximately, from the ground surface down to the competent formational soils (Figures 5 and 6). The intent of the soil cement zones was to mitigate the poor support characteristics of the alluvial soils within pre-existing channels under the PGR wall.

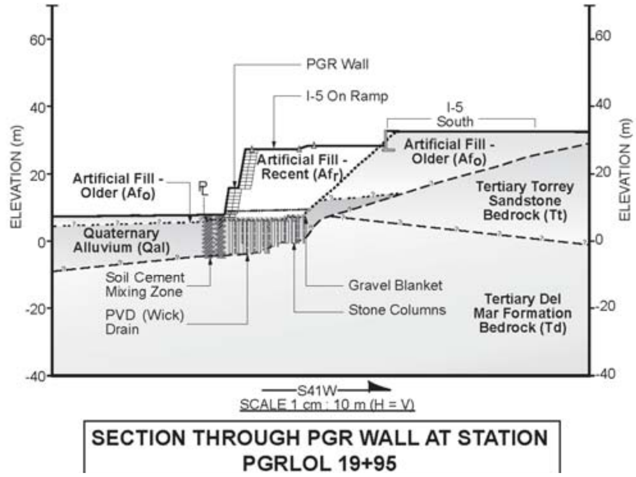


Figure 5 - Section through PGR Wall

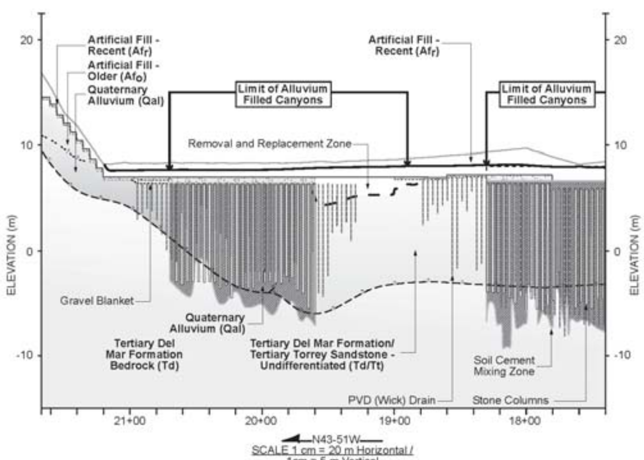


Figure 6 - Transverse Section Through Northern Portion of PGR Wall

Stone columns are generally located east of the zone of soil cement mixing between Stations 13+70 to 18+30 and the wick drains are located between Stations 13+50 to 18+30 and Stations 19+60 to 20+70. The Gravel Drainage Blanket extends northerly across the tops of the stone columns to near Station 19+00, and resumes at approximately Station 19+60. The primary purpose of the stone columns was to mitigate a moderate to high potential liquefaction of alluvial soils in pre-existing drainage channels that underlie the PGR wall. The stone column installation was intended to provide densification of these soils and to provide vertical (upward) drainage path to relieve increased soil pore pressures during an earthquake event. In order to dissipate pore pressures during an earthquake event, the stone columns were topped with a gravel blanket. During an earthquake event, relief of pressurized water buildup within stone columns should occur by upward drainage and dissipation across the gravel blanket.

CONCEPTUAL MODEL OF THE EFFECTS OF ENGINEERED STRUCTURES ON LOCAL HYDROLOGY

The expansion of the I-5 freeway led to a significant increase in hardscape area along with a greater volume of runoff draining toward the 54 inch (1.4 meter) storm drain pipe located at the north end of the subject property. Part of the PGR wall construction near Station 21+40 included extension of the existing 54-inch (1.4 meter) concrete storm drain pipe to the channel that extends along the length of the north boundary of the site. This pipe was extended approximately 55 feet (16.7 meters) toward the site and is underlain by a gravel bed installed as part of the design and construction. The extension of the storm drain has resulted in an angled point of entry into the channel. No splash wall was provided at this point, thereby allowing the channel to be overtopped during some storm events. At the downstream portion of the channel, reeds and vegetation clogged the channel and significantly diminished its capacity during storm events. Absence of a splash wall and accumulation of vegetation in the lower reach of the channel resulted in overtopping and significant flooding of the buildings at the northwest corner of the site in January 2010.

During dry weather, nuisance flows create a continuous stream of water through this storm drain and ditch. In places, the culvert and ditch have been cracked allowing some water to seep downwards toward the water table. On the other hand, a video camera survey inside the culvert also revealed water spurting into the culvert through a joint beneath the east side of the freeway, indicating groundwater around the exterior of the culvert in this area. This groundwater appeared to be perched water on the bedrock beneath the freeway, flowing toward the culvert from the north and south. Perched groundwater in the fill material surrounding the culvert would flow west and likely seep into the gravel leveling pads on the south end of the PGR wall; these gravel beds stair-step downward from the 54-inch (1.4 meter) storm drain toward the northeast corner of the industrial park (Figure 6).

Construction of the PGR wall resulted in increased surface runoff to the site by replacing a portion of landscape previously occupied by unimproved slopes with hardscape surface with a higher runoff coefficient. A wide drainage terrace constructed on the PGR wall directed surface water from the PGR wall onto industrial park property through sheet flow. This condition was partially mitigated by installation of an asphalt curb along the right of way that re-directed water to the lowest point of the industrial park property where the water sheet flows across the asphalt parking lot.

In summary, the modified surface water drainage has the potential to impact groundwater by locally increasing recharge from a) flood water overtopping the ditch fed by the 54-inch (1.4 meter) storm drain, b) seepage through cracks in the culvert and ditch, c) drainage outside the 54-inch (1.4 meter) storm drain which is intercepted in the subsurface by the gravel leveling pads of the PGR wall, and d) infiltration of rain and runoff from the PGR wall

Additionally, irrigation of vegetation on the PGR wall and subsequent drainage also could be expected to increase recharge locally along the base of the wall. Irrigation began in June 2007 at a rate of as much as 80,000 cubic feet per month (74.4 cubic meters per day) and continued through November 2008. Following about a year of stable conditions, a piezometer near the industrial park installed within the PGR wall base showed a water level rise of about 2.5 feet (0.8 meters) beginning in the summer of 2007. Several seeps were observed at the toe of the PGR wall. Electrical conductivity measurements in monitor wells in the industrial park downgradient support the interpretation of a contribution of local recharge to groundwater from irrigation on the newly constructed PGR wall.

The construction of the PGR wall also would be expected to modify the subsurface hydrology. First, construction of the soil cement wall through the alluvium of the historic tributary canyons would have the effect of impeding westward flowing groundwater. The hydraulic conductivity measured in the laboratory on samples of the soil cement is about 0.003 ft/day (1.1×10^{-6} cm/s), whereas that of the alluvium is as much as 25 ft/day (8.8×10^{-3} cm/s), based on aquifer pumping tests. Second, the stone columns and vertical drains, where installed into bedrock and deep alluvium, would serve as conduits allowing the rise of groundwater under pressure. Third, the gravel blankets and leveling pads would collect water impeded by the cement wall, together with rising water in the stone columns and vertical drains, and facilitate transport of this water laterally within the gravel to lower elevations.

Despite rising groundwater encountered during and after construction of the PGR wall, no subdrainage system was installed that would provide drainage to the gravel blanket. This gravel blanket and some of the fill soils that comprise the PGR wall are currently inundated with water, rendering the drainage blanket ineffective for its intended purpose; namely, drainage of the stone column system during an earthquake event. Groundwater collected by the gravel blanket and leveling pads can only escape by flowing over the top of the cement wall and/or leaking into the surrounding native alluvium and fill.

Two gaps in the mechanically stabilized (MSE) wall foundation occur on the north and south end of the industrial park area (e.g., Figures 1, 2, 4) which was affected by the shallow groundwater. Water table elevation data show that ground water flow emanates from these gaps and from the northeast corner of the site near the 54 inch (1.4 m) storm drain.

GROUNDWATER SIMULATIONS OF EFFECTS OF MSE WALL

In order to confirm that construction of the MSE wall could potentially cause groundwater levels to rise downstream of the MSE wall, we developed a three-dimensional groundwater model using Modflow Surfact (Hydrogeologic, 1998).

The model simulation was divided into three different runs. The first run of the model was a steady state run that represented water level conditions at the site before the engineering work took place (groundwater conditions as they existed before 2003). The second run of the model was a transient simulation that ran for a two-year period (2003 and 2004) where only the soil cement wall was installed (other features such as the stone columns and gravel drainage blankets were not included). The third run of the model was another transient simulation that ran for a five-year period (2005 to 2009) that started immediately after the PGR wall and therefore included the soil cement wall, stone columns, gravel blanket, as well as the PGR wall and the newly paved highway. Final heads of the first run were used as initial heads of the second run, and final heads of the second run were used as initial heads of the third run.

The plan view of the model included an area of approximately 4,950 feet (1509 m) by 3,050 feet (930 m) and is divided into 150 grid cells by 93 grid cells, each with dimension of 33 feet (10 m) by 33 feet (10 m). In the vertical direction, the model consisted of 15 layers; the top of the first layer of the model represented the ground surface elevation. A constant head boundary was assigned to the west model boundary along the surface water drainage in the Los Peñasquitos Lagoon. A constant flux boundary was assigned to the eastern and southern model boundaries to accommodate for groundwater underflow towards the ocean. The amount of flux into the model was treated as a calibration parameter in the first run (the steady state model) to achieve a good match between simulated and the pre-2003 observed groundwater elevations and was kept constant in the subsequent two modeling runs.

Recharge from precipitation was assumed to be constant all over the domain and equal to 0.2 inches per year (5 mm/yr), which is approximately 2% of annual precipitation in this area. However, this recharge was enhanced in several areas at the PGR wall during specific time periods when the wall was being constructed as a result of the original hillside on the western side of the highway being excavated and plants being removed and ground surface being flattened. Recharge from the 54-inch (1.37 m) storm drain pipe was included in the second and third runs of the model.

General Head boundaries (GHB) were assigned to the model bottom to represent upward flow to the model from the bedrock underneath. The conductance of the GHB was taken small enough in the first modeling run, allowing minimal upward flow under normal steady state conditions. Conductance of cells representing areas occupied by the stone columns was increased by three orders of magnitude in the third run of the model, consistent with the high vertical hydraulic conductivity of these cells that permit increased upflow from the bedrock.

Horizontal hydraulic conductivities of different geologic formations were taken within the range of reported values of such formations in the literature. Values in the model ranged between 0.2 ft/day (7 x 10^{-5} cm/s) in the bedrock to 33 ft/day (1.1 x 10^{-2} cm/s) for sand and gravel. Vertical hydraulic conductivity was assumed to be one-tenth of the horizontal hydraulic conductivity. The specific yield for bedrock and alluvium formations was assumed to be 0.05 and 0.1, respectively. For the engineered materials, the horizontal hydraulic conductivity of the soil cement wall zone was assumed 0.01 ft/day (3.5 x 10^{-6} cm/s) and of cells representing stone columns and gravel blanket, it was assumed as 1,000 ft/day (0.35 cm/s).

To assess the water level rise caused by the I-5 Freeway expansion, the heads of the first run, which represents steady state conditions, were subtracted from simulated heads at the end of the third run. The difference in these groundwater elevations is the change in water elevations from the pre-2003 to post-2009 conditions (Figure 7). Figure 7 shows that the installation of the soil cement wall, stone columns, gravel blanket and/or leveling pad, the PGR wall and additional paving have caused a 4 to 5 foot (1.2 to 1.5 m) rise at downstream MSE wall. The difference between the simulated pre-2003 and post-2009 groundwater elevations was compared to measured values and a good match was observed at different locations.

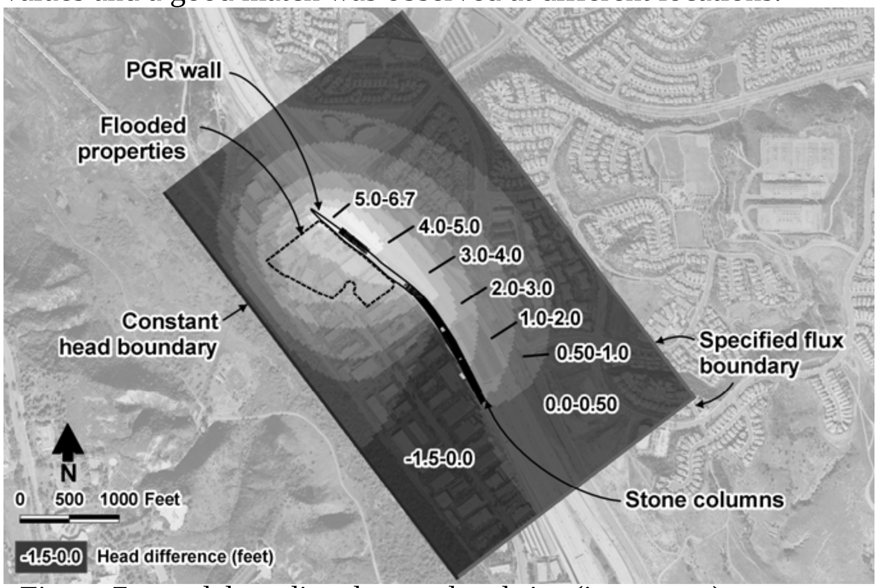


Figure 7 - model predicted water level rise (in process)

CONCLUSIONS

Hydrogeological data and groundwater modeling indicate that the source of rising groundwater in an industrial park downgradient of a highway expansion was caused by the construction of a mechanically stabilized PGR wall, along with other factors related to site drainage and irrigation on the wall. The foundation collected groundwater from over more than 1000 feet (305 m) along the wall and focused the flow onto the affected property, causing the groundwater table to rise in this local area. Increased surface water runoff and flooding caused by the construction also contributed to the shallow groundwater problem. The rising groundwater condition could have been anticipated by incorporating hydrogeological site characterization, groundwater modeling, and analyses of potential hydrological effects into the initial design.

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