

# Ground Subsidence Associated With Dewatering of a Depressed Highway Section

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Subsidence of land areas adjacent to construction of an Interstate highway is reported. Foundation settlements of structures adjacent to a depressed section occurred as a result of pumping groundwater during construction dewatering operations. Preliminary recommendations and actual construction dewatering operations are discussed. The stability of the Sacramento River levee and the possibility of piping during high water were significant factors in planning the dewatering operation. Records of groundwater drawdown for various pumping rates are presented with data from a Ranney well pumping system located in downtown Sacramento; foundation settlement studies for buildings in the adjacent area and specifications for dewatering of the depressed highway section are described. The need for comprehensive laboratory and field tests is discussed. Unforeseen circumstances that developed during the dewatering process required deviation from the scheduled construction operations and continuous monitoring of groundwater and ground surface elevations. It is concluded that the settlement problem could have been minimized had its probability been more fully realized. Groundwater levels should have been more closely monitored during the initial stages of dewatering. Valuable information could have been developed early in the planning stages of this project from drawdown studies using deep wells pumping from a lower, more permeable stratum.

Land subsidence is a normal occurrence in many areas of California. For example, in the Santa Clara and San Joaquin Valleys, deep subsidence has resulted largely from the compaction of soil deposits caused by accelerated pumping of groundwater for agricultural purposes (1).

The general lowering of the groundwater table by dewatering to provide dry conditions during work in large open excavations can also induce land subsidence or soil settlement, which is detrimental to structures above the affected water table. Even when appropriate precautions are taken during dewatering operations, unforeseen events or conditions sometimes occur. When the water table is lowered, the effective load on the subsoil is increased by an amount equal to the difference between the drained and submerged weights of the entire soil mass between the original and the lowered water

table. This increased overburden pressure causes additional compression and produces settlement (2). Settlement can occur rapidly in sands, but in clays and silt soils a much longer period of time is involved.

This report presents a case history of a ground subsidence that occurred during dewatering for construction of a depressed highway section in Sacramento.

## BACKGROUND INFORMATION

During 1968 a section of Interstate 5 was constructed as a depressed freeway through the old historic area of Sacramento (Figure 1). This portion of freeway is adjacent to the Sacramento River, which traverses the westerly edge of downtown Sacramento. The design planned for construction of a 1220-m (4000-ft) depressed roadway, approaching, at one point, within 37 m (120 ft) of the river.

The city of Sacramento is protected from flooding by a system of levees along the Sacramento River on the west and the American River on the north. Because of the proximity of the river and the adjacent levee system, several safeguards were included in the depressed freeway design, along with stringent specifications and construction requirements. The area to be depressed was designed as a boat section to resist buoyant forces, with portland cement concrete up to 3.7 m (12 ft) in thickness. At the higher roadway elevations, the uplift was resisted by the weight of the concrete structure alone, but in the deepest excavation section, tension or hold-down piles were used to resist the main portion of the uplift forces and achieve economy with a thinner concrete section.

The river stage on the Sacramento River during periods of low runoff is 1.5 to 3 m (5 to 10 ft) above mean sea level. At times during the winter, it reaches 7.6 m (25 ft) and possibly higher. The average elevation of the ground surface in the downtown area is about 4.9 m (16 feet). The top of the levee is 9.8 m (32 ft) above sea level.

The low point of the finished grade in the depressed section was at about -0.6 m (-2 ft) below sea level, but excavation was required to -2.6 m (-8.5 ft) and slightly lower. Excavation for the pumping station to drain the completed facility extended down to -5.5 m (-18 ft).

Soils in the area are moderately heterogeneous. In the southerly half of the depressed section above sea level and in the northerly half above -3.0 m (-10 ft) there are silty clays and clayey silts. These are interbedded with lenses and layers of sand and silt. Underlying these mixtures are sands and silty sands with gravel occurring at depths down to -12.2 m (-40 ft).

The stability of the levee and the possibility of piping during high water periods were prime concerns, and stringent specifications were proposed to prevent problems in this area during construction. Attention was also focused on the effects of dewatering and the possibility of subsequent settlement of certain designated buildings adjacent to the work. Specifications relating to the protection of these specific buildings were formulated. The contractor was also required to inspect and record the existing condition of these buildings prior to working in the vicinity, and to replace or restore any subsequent damage.

As the project proceeded to the bidding stage, a consultant hired by the California Department of Transportation reviewed the plans and specifications with respect to their adequacy in ensuring levee safety and maintaining existing flood protection. It was recommended that the excavation work be done in the dry condition, which required dewatering of the excavation and construction of a cofferdam.

The special provisions had several requirements relating to groundwater control:

1. The silt production of a pumping well after a 48-h developmental period was to be no more than 5 ppm;
2. At river stages below 3 m (10 ft) groundwater could be lowered as necessary to continue the work;
3. At river stages between 3 and 7 m (10 and 24 ft) work could continue in the dry condition as long as the bottom of the excavation stayed above an imaginary plane sloping away from the river surface on a maximum 5 percent gradient;
4. When the river stage was above 7.3 m (24 ft), all dewatering was to stop;
5. Relief wells were to be placed inside the cofferdam and were to be of sufficient capacity to raise the water level in the excavated area at a rate of 9 cm (0.3 ft)/h under a 3-m (10-ft) head; and
6. Additional means of flooding the excavation were to be provided in conjunction with the relief wells so that the water level in the excavation could be raised at the rate of 12 cm (0.4 ft)/h, which would keep pace with the expected maximum rate of rise of the Sacramento River.

## THE DEWATERING OPERATION

Sheet piling was placed around the entire excavation area and the groundwater lowered by pumping from a deep, relatively pervious gravel stratum (rather than from a shallower well point system). A total of 29 pumps, each rated at about 7.6 m<sup>3</sup>/min (2000 gpm), were used around the periphery of the excavation. The well casing extended to about -18.3 m (-60 ft) below sea level with a pump pickup of -12.2 m (-40 ft). The tip elevation for the sheet piling was about -7.6 m (-25 ft).

A cross section of the excavation is shown in Figure 2 with the location of the intake wells, the adjacent Sacramento River and levee embankment, the normal groundwater table sloping away from the river, the groundwater table during dewatering, and the soil profile. The silt production from the wells was a maximum of 2 ppm, which was less than the allowed maximum of 5 ppm. The intake wells were located on both

sides of the excavation although the majority were on the easterly side.

The dewatering operations began with three pumps in operation on August 20, 1968. Other pumps were gradually put into operation until, about 20 days later, 16 pumps were producing an estimated 60 m<sup>3</sup>/min (16 000 gpm). During this time, the water table was lowered from about 0 to -6.7 m (-22 ft). No water table observations were made during the early stages of dewatering since observation wells were not yet complete. (Existing wells were available but were not used.) It is therefore probable that the drawdown exceeded the maximum recorded low. The pumping rates and the resulting changes in groundwater levels along O Street over an 18-month period following the start of dewatering are shown in Figure 3.

About 15 days after pumping began, tenants in a building situated about 250 m (800 ft) from the nearest line of pumps noticed building distress. Reports of damage in other buildings came in rapidly, and it soon became apparent that settlement was taking place over a fairly wide area. The pumping was then reduced to an estimated rate of about 34 m<sup>3</sup>/min (9000 gpm). As a result, the water table at the excavation rose from -6.7 m (-22 ft) to -4.9 m (-16 ft). At this same time, the California Department of Transportation began drilling a series of additional sample borings and observation wells, and level circuits were established to monitor elevations in the adjacent downtown area. This information was used to supplement the data that had been gathered during an extensive program of foundation exploration, drawdown testing, and laboratory soil testing prior to the actual design and construction.

A review of the buildings in the settlement area showed that pile-supported structures had not settled significantly and that buildings on spread footings had sustained only isolated minor damage. The damage that had occurred was due mainly to differential settlement in buildings whose structural elements were founded on piles and whose bottom story floors and walls were grade-supported on compacted earth. Damage had also occurred where peripheral sidewalks and similar appurtenant structures were in contact with pile-supported structures.

The settlement graphs (Figure 4) for benchmarks located along Second Street show that about 3.4 to 7.9 cm (0.11 to 0.26 ft) of settlement occurred during September 1968. About 1.8 cm (0.06 ft) of additional settlement occurred during the 1-year period following the initial drawdown. However, the benchmark elevations are influenced to a major degree by cyclic changes in the groundwater table due to the river stage and recharge from rainfall. Historically, they have varied  $\pm 0.9$  cm (0.03 ft) annually.

## ANALYSIS OF THE PROBLEM

Groundwater observations made at various locations in Sacramento over a period of years have indicated a probable historical low water table of 0.9 to -0.9 m (3 to -3 ft), depending on the distance from the river. The normal water table gradient prior to the excavation and the dewatering operation sloped away from the river as shown in Figure 2. After one month of dewatering, the water table varied from about -4.9 to -2.4 m (-16 to -8 ft) and sloped toward the excavation. In the area where settlement was first noticed, the difference in groundwater level was 4.9 m (16 ft).

Data from various sources were gathered to obtain a better picture of the foundation soils and their consolidation and permeability characteristics in the downtown area. Old boring logs and tests made by the transporta-

Figure 1. Project location map of depressed section.

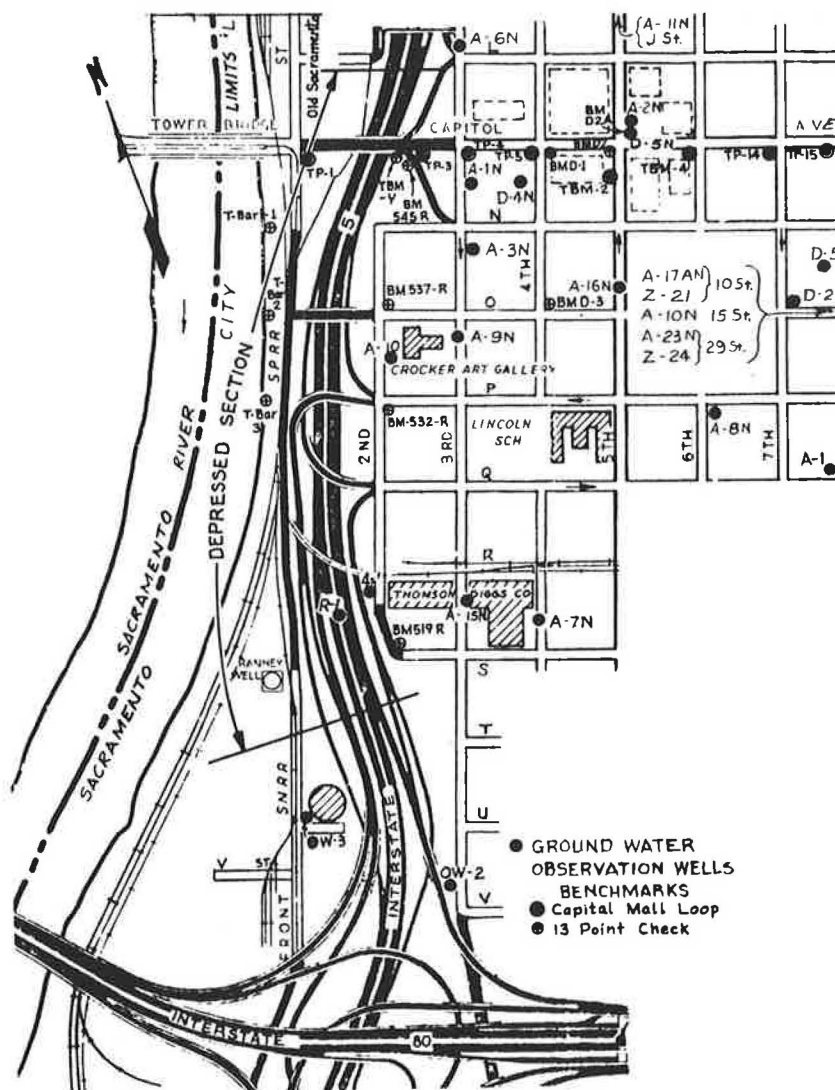
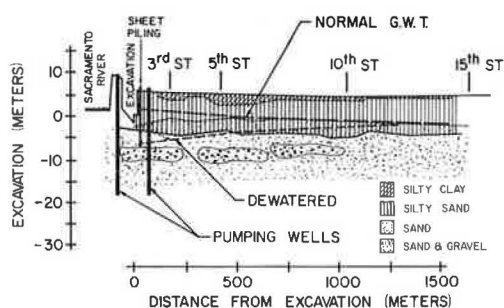


Figure 2. Cross section of excavation.



tion laboratory for state buildings in the area were examined. Foundation reports for major structures in the affected area were also obtained from the Sacramento City Engineer's Office.

The lowering of the groundwater table in the general area was complicated by the fact that several other well systems, including the new state central heating and cooling system, were also pumping from wells in the same general area. The heating and cooling system uses a Ranney well installation that went into service during the initial stages of the dewatering operation

and was pumping at a rate of about  $11.4 \text{ m}^3/\text{min}$  (3000 gpm) on September 19, 1968, with rates of about  $22.8 \text{ m}^3/\text{min}$  (6000 gpm) during various 8-h periods. The main well for this collection system is located immediately west of the freeway near S Street as shown in Figure 1. Groundwater observations and pumping rates for this system are shown in Figure 5. The Ranney collector system at this location consists of a 6.1-m (20-ft) diameter caisson driven to -21.6 m (-71 ft). At -18.3 m (-60 ft), six laterals 25.6 to 36.3 m (84 to 119 ft) in length radiate outward toward the river.

Elevation measurements of benchmarks located along the Capitol Mall Loop (Figure 1) suggest some continuation of settlement after the initial drawdown in September 1968. Changes in the ground surface elevation are shown in Figure 6. The maximum drop in elevation varied from 3.1 cm (0.10 ft) nearest the excavation to about 0.3 cm (0.01 ft) near Eighth Street. This settlement occurred over a period of 1 year following the initial drawdown of the water table. The pattern of the ground surface elevation fluctuations indicated by the benchmark measurements closely follows the normal cyclic changes in groundwater levels due to changes in river stage and recharge by rainfall.

Figure 7 shows the relatively flat drawdown curve (curve C) that resulted from pumping groundwater from the deep, relatively pervious gravel stratum (Figure 2).

Figure 3. Groundwater levels (along O Street) and pumping rates.

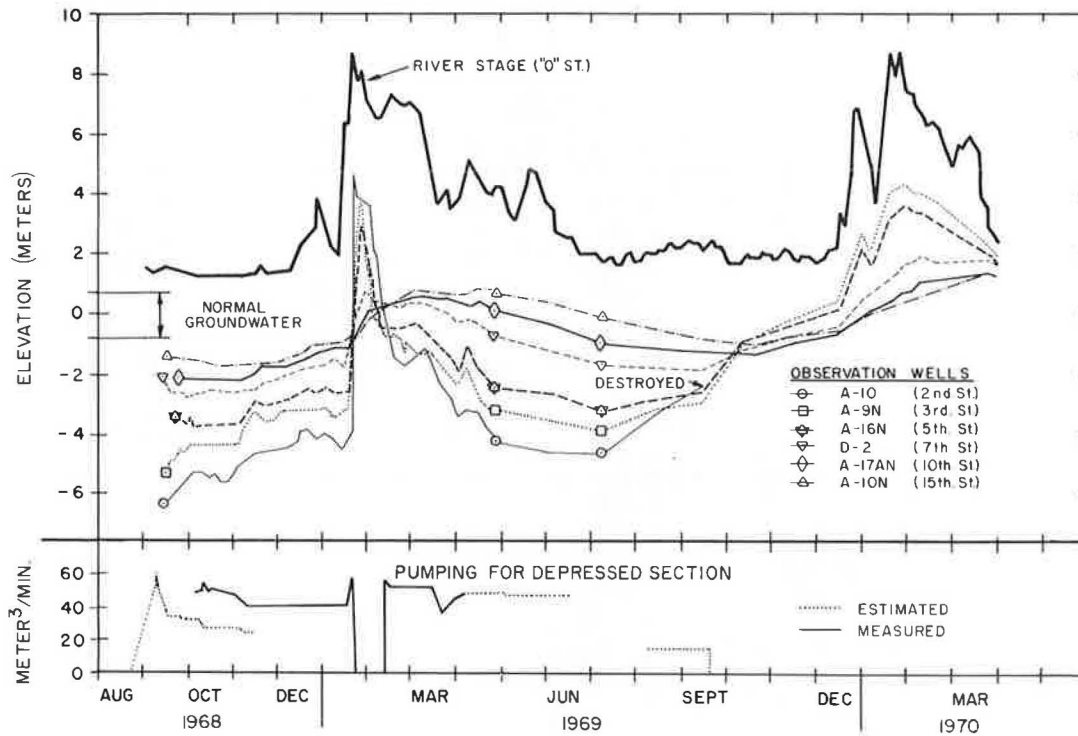
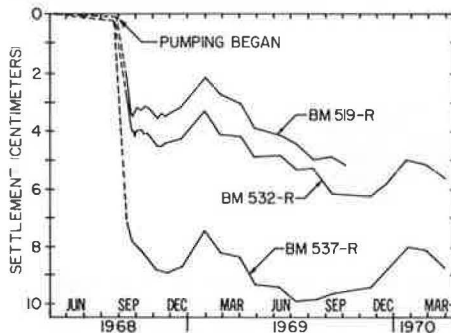


Figure 4. Change in benchmark elevations (Second Street).



Earlier groundwater studies had been based on wells that pumped at a much shallower depth in a less permeable layer, and resulted in a much sharper drawdown curve (curve A). Curve B illustrates the drawdown curve that was developed during contract pump tests prior to construction using a single deep well founded in the underlying permeable layer with water recharge from below the drawdown cone. The pumping rates were approximately 4.6 and 6.8 m<sup>3</sup>/min (1200 and 1800 gpm).

Supplemental consolidation tests using undisturbed soil samples of the silt and silty sands located near the area of greatest reported distress were performed to analyze the settlement problem. Settlement calculations were based on the increased effective overburden pressure resulting from the lowering of the water table. It was assumed that historically the water table had a previous low of 5.2 m (17 ft) below the ground surface and that the underlying soil had been preconsolidated by this condition. Settlement was then calculated with the water table lowered as much as 6.1 m (20 ft). The results of these calculations for various applied building loads are shown in Figure 8.

The calculated settlements are of the same relative magnitude as the reported drop in benchmark elevations in the affected area (Figure 4) and confirm that the rapid settlement had occurred in the silt and silty sand deposits.

An evaluation of the situation was made soon after the initial settlement was detected and the initial data could be analyzed. It was concluded, based on precision follow-up ground surface elevation measurements and settlement calculations, that the situation had stabilized and that no additional significant settlement would occur as a result of higher pumping rates during high river stage if the groundwater table beneath the excavation was maintained at about the same level. It was also felt that pile-supported structures would not settle as a result of downdrag or any other consequence of the dewatering activities. The contract specifications were also considered adequate to ensure protection of Sacramento during expected high river stages. It was decided to continue pumping in the dry condition as long as the river stage was between 3.0 and 7.3 m (10 and 24 ft), and to provide standby power: The excavation would be flooded when the river reached 7.3 m (24 ft). It was also recommended that the maximum differential in head between the water in the river and the water in the excavated section not exceed 2.4 m (8 ft).

During January 1969, high water stage in the Sacramento River reached 8.5 m (28 ft) and remained there for about 24 h. Dewatering was stopped and the excavation flooded by pumping directly into the excavation. The elevation of the water in the excavation stabilized at approximately 3.7 m (12 ft) shortly after the high river stage. Flooding the excavation provided the necessary counterbalance of excess hydrostatic pressures in the bottom of the excavation. The performance of the section under these conditions indicates that the specification requirements are conservative and provide adequate protection for the city.

Six days after flooding, dewatering was resumed with



Figure 5. Groundwater levels (along S Street) and pumping rate for Ranney well.

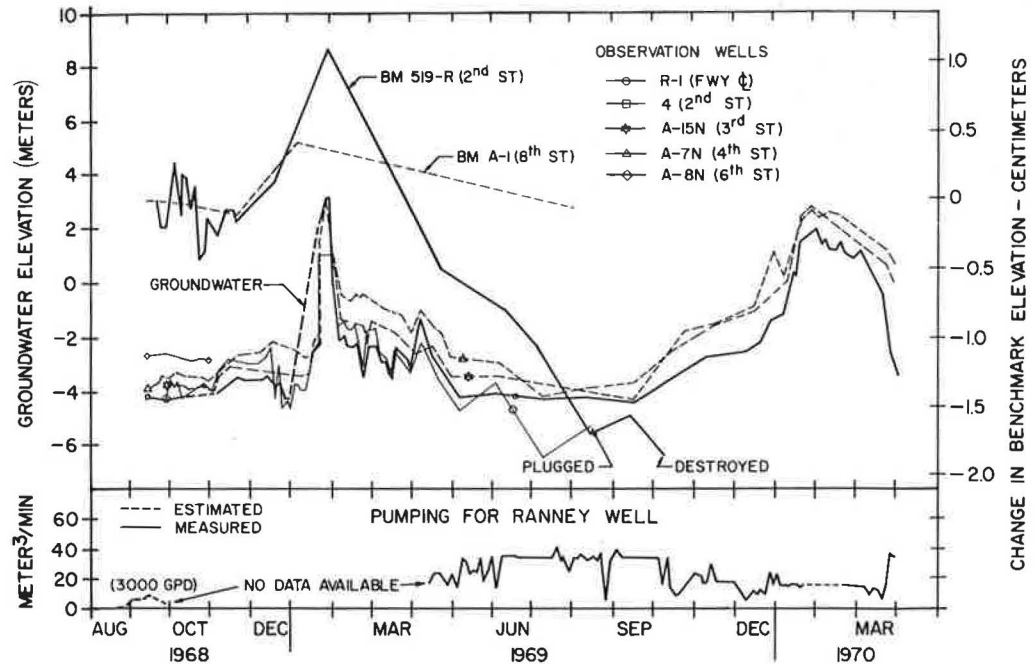


Figure 6. Settlement and groundwater elevation (Capitol Mall Loop).

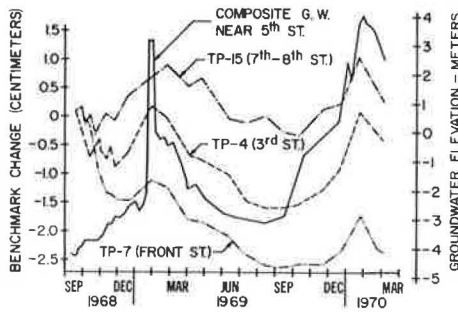


Figure 7. Drawdown test results.

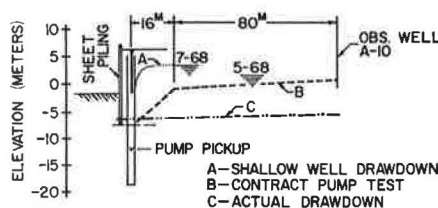
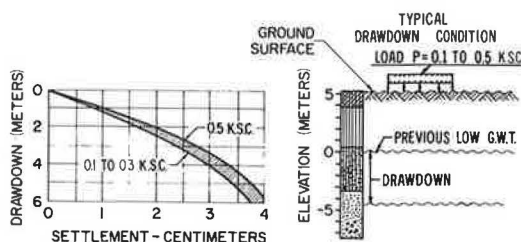


Figure 8. Settlement due to drawdown.



no complications, and construction continued with no further subsidence under adjacent structures.

## SUMMARY AND CONCLUSIONS

1. Even when appropriate precautions are taken during construction dewatering operations, unforeseen events or conditions may occur and require deviation from planned construction.
2. Wide fluctuations in groundwater levels can result in ground subsidence.
3. Closer monitoring of groundwater during the initial stages of dewatering is recommended for future construction projects.
4. Subsidence could have been minimized on this project by pumping from closely spaced well points at a shallower depth.
5. If the original preliminary test data had not been misinterpreted, the probability of subsidence would have been more fully realized.
6. Valuable information could have been established early in the planning stages of this project from drawdown studies using deep wells pumping from a lower, more permeable stratum.
7. The specification requirements were appropriate; adequate stability of the river levee system and flood protection of Sacramento during high river stages were provided.

## ACKNOWLEDGMENTS

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