Proceedings of the Canadian Society of Civil Engineers Annual Conference, Regina,
Saskatchewan, Canada. June 2-5, 1999

SUBSIDENCE IN THE CITY OF HANOI, VIETNAM

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ABSTRACT

A study of land subsidence due to pumping in the city of Hanoi, Vietnam, was conducted by collecting and analyzing data on the geology, hydrology, soil properties, and observed settlements. The city of Hanoi is underlain by sediments consisting of clay, silt, mud, peat, sand, and gravel. The pumping of groundwater causes consolidation of compressible aquitard layers. The water demand is increasing with time for the city of Hanoi. The present total water pumping is 450,000 m^3/day and by the year 2010, the proposal is to increase the rate to 751,000 m^3/day. This research program involved the modelling of groundwater flows, seepage analyses due to pumping, and stress-deformation analyses. The effect of surface infiltration was also modelled. The computed settlements in parts of the city of Hanoi were compared to the results of measurements of settlement in the city area. The simulation results appear to be in were fairly good agreement with the measurement results. The study showed that subsidence due to groundwater pumping is a serious problem in the city of Hanoi. In the future, it is important to continue to measure settlements and compute possible deformations associated with actual rates of pumping.

General Conference, Geotechnical Engineering

1.0 INTRODUCTION

Hanoi, Vietnam, is a city of more than 4 million people located in the delta area of the Red River. The city is situated about 100 km from the Gulf of Tonkin. The population growth and technological developments in Hanoi have produced a continuously increasing demand for potable water. The water for domestic and industrial use in Hanoi comes from wells located within and around the city. The heavy pumping of groundwater has produced a serious problem of subsidence, which in turn has affected the surface structures in the city of Hanoi. Areas of land subsidence due to groundwater pumping are underlain by deposits of highly compressible soils. The soils are Quaternary and younger in age, and are mostly alluvial and lacustrine in origin with low coefficients of permeability and high compressibilities. The aquifers are confined and comprise sands and gravel with high coefficients of permeability and low compressibilities. The city of Hanoi has been extracting water from aquifers since 1909. Although the present total water withdrawal is only about 450,000 m^3/day, there have been signs of distress on some of the buildings from ground subsidence. Some buildings, roads and other structures in the areas of pumping have been damaged by settlement, which is assumed to be induced by the groundwater extraction. Measurements of ground movement within the city of Hanoi would indicate that the pumping of groundwater in the cause of the subsidence.

This preliminary study of subsidence due to the pumping of groundwater is based on general information concerning site conditions in the city of Hanoi and soil investigations conducted at some of the well-fields. The main objective of this study is to document the evidence related to the subsidence problem in the city of Hanoi.

Due to of the difficulties in obtaining relevant data, the scope of the work is limited to the compilation and analysis of existing field data. The amount of available data does not allow for a detailed analysis of all of the water extraction well systems. As a result, there is a limit to the amount of information that can be provided regarding possible subsidence in various parts of the city of Hanoi.

2.0 MODFLOW ANALYSIS

The assessment of land subsidence in the Hanoi area is closely related to the study of groundwater movement. Modflow has been recognized as a general purpose, three-dimensional, finite difference, groundwater flow model that allows for a variety of input and boundary condition options.

The groundwater model was applied to the entire city of Hanoi. The ground surface and the surface of the layers in the model were synthesized based on well logs, geological and topographic information. In the area where the pumping wells are located, a square cell 125 m by 125 m was chosen for discretization. For the peripheral area which is not influenced significantly by pumping, the discretization cells sizes are 250m by 250m, 500m by 500m, and 1000 m by 1000m. The discretized flow model consisted of about 42,840 cells with three layers covering an area of 30 km by 29 km.

Pumping from the aquifer layer was simulated using the "Well" package of Modflow for individual cells located within the southern part of the Red River basin in the city of Hanoi. Well extraction rates were assigned to cells representing the pumping wells in layer three (i.e., sandy gravel). Future groundwater exploitation from within the city of Hanoi was also simulated. The capacity of the well-fields and the locations of the well-fields were adopted from the proposal of the City Council Water Master Plan Hanoi, up to year 2010 when the proposed total extraction will be 751,000 m^3/day.

Well data measurements for the period from 1988 to 1995 were used for calibration of the model. The calibration of the pumping groundwater model was an integrative process. The surface infiltration and material properties for each hydrostratigraphic unit, were refined until the simulated hydraulic head distribution closely approximated measured values. The calibrated hydraulic parameters are those values that produced a flow model that most closely represented the measured regional hydrogeologic conditions and responses. The calibration parameters fell within the range of measured values from soil samples.

A transient flow analysis was performed for the study area. The hydraulic head and the drawdown were computed for the period from 1974 to 2015. It was assumed that the initial head was constant in each layer at an elevation of 3.8 m above mean sea level. Figure 1 shows the contours heads calculated using Modflow. The Modflow results show depressions in the pumping well regions that are similar to the measured values.

Figure 2 presents a plot of the simulated heads versus the measured heads in 1995 for the Maidich, Ngocha, Ngosilien, Luongyen, Tuongmai, Hadinh and the Phapvan well-fields. The data shows that the calculated and measured values are close.

3.0 AXI-SYMMETRICAL ANALYSIS OF SEEPAGE AT THE PHAPVAN WELL-FIELD

The Phapvan well-field in the city of Hanoi was selected for the axi-symmetric seepage analysis modelling. Numerical simulations of subsidence can either be conducted using a coupled or uncoupled consolidation theory approach. The modelling results presented in this study are of an uncoupled nature with respect to continuity and equilibrium. The pore-water pressure change results were used in a stress/deformation analysis model (i.e., Sigma/W software package) to calculate settlement.

The characterization of the pore-water pressure conditions is essential to the prediction the settlement due to groundwater pumping. Pore-water pressures were estimated through the use of steady state and transient analyses using the Seep/W computer model software. The pore-water pressure results were then imported into the stress/deformation analysis to compute settlement.

The matrix form of the axi-symmetric seepage analysis for a steady state analysis is as follows.

[Eq.1] *[K] {H} = {Q}*
where:
[K] = element characteristic matrix,
{Q} = applied flux vector, and
{H} = vector of nodal heads.

3.1 Steady State Flow Model

The characterization of the initial and final pore-water pressure profiles is an essential part of a stress/deformation analysis. Steady state and transient conditions can be considered. The results from the seepage analyses were imported into the stress/deformation analysis to estimate the subsidence due to pumping groundwater. The steady state condition provides an initial data file for the transient flow analysis process. Steady state, axi-symmetric analyses were conducted for the Phapvan well-field.

3.2 Boundary Conditions

The geometric meshes for the Phapvan and Maidich model are shown in Fig. 3. All elements in the mesh are quadrilaterals with 4 nodes or 8 nodes and triangular with 3 nodes. The elements at the edge of vertical boundary on the right side (i.e., farthest away from the well) were considered to be infinite elements.

The computer program called SoilCover (Wilson et al., 1997) was used to model the surface flux boundary as a percentage of the mean annual precipitation. SoilCover is a soil-atmosphere flux modelling software package. The net infiltration from SoilCover is only about 2% of the annual precipitation or 7.93×10^{-10} m/s. A constant flux of 7.93×10^{-10} m/s was applied to all surface nodes in the model.

The vertical boundary head at both sides of the model (i.e., right and left side) were assumed to be constant head boundaries below the water table. The heads were assumed to be equal to the elevation of the initial heads from the Modflow model. The vertical head boundaries at the left and right hand side of the model were 3.80 m and 3.75 m, respectively.

Quantitative information concerning aquifer characteristics is available from the results of pumping tests carried out at various locations in the city of Hanoi (Minh et al., 1993). The coefficients of permeability of the aquitard layers were based on the data from the soils reports and laboratory testing of undisturbed soil samples at the University of

Saskatchewan, Canada. The coefficients of permeability indicate that the aquitards have a low coefficient of permeability (i.e., approximately 4×10^{-9} m/s), and aquifer has a high coefficient of permeability (i.e., approximately 6×10^{-4} m/s). The calibration for the coefficients of permeability was achieved by selecting a series of values within the range of field measured values. The coefficient of permeability values that best simulated field responses were chosen for the steady state and transient flow model. Table 1 provides a comparison of the calibrated model parameters and the measured values.

Soft soil layers compress as a result of groundwater withdrawal. The pore-water pressures drop in the soil and cause an increase in effective stress. Therefore, pore-water pressures are basic to the evaluation of ground subsidence. A transient groundwater analysis was performed to determine the pore-water pressure dissipation with time and the subsequent subsidence due to groundwater lowering. The boundary conditions in the transient model are the same as those described for the steady state model with the exception that heads are used along the vertical boundaries. The boundary condition at the well (i.e., left hand side of the model) were taken from results of the Modflow model. The material properties used in the steady state analysis were also used in the transient analysis. A storage function for the silty clay layer was estimated. The storage functions were estimated by the method described by Fredlund et al. (1994). Unsaturated coefficient of permeability functions were defined for the upper soils. The coefficient of permeability of the materials that remains saturated was represented as a constant value. The coefficient of permeability function for the unsaturated material was estimated using an approximate soil-water characteristic curve and the method described by Fredlund et al. (1994).

4.0 RESULTS OF THE TRANSIENT ANALYSIS

The results of the seepage analysis are presented in the form of pore-water pressure contours. The pressure head profiles generated due to the lowering of the groundwater at the Phapvan well-field are shown in Fig. 4. The pressure head profiles are consistent with consolidation theory results assuming single drainage of the layer. Comparing the results of the pressure head in the sandy gravel with the pressure heads of the aquifer layer in the Modflow model shows that there is some different between the Modflow and axi-symmetric seepage analysis. Because of the boundaries condition in the Modflow and axi-symmetric were different. The boundary condition for the axi-symmetric seepage analysis was a constant head at the well, while in the Modflow analysis, there was a constant rate of the pumping. The differing boundary conditions are probably the primary reason for the variation in the results mentioned above.

5.0 STRESS/DEFORMATION ANALYSIS IN THE VICINITY OF THE PHAPVAN WELL-FIELD

An increase in effective stress results in the consolidation of compressible sediments. The withdrawal of water from the wells reduces the pore-water heads in the aquifers and increases the effective stresses. A change in effective stress occurs if the seepage stress across the bed is altered in direction or magnitude. The behavior of natural soils under such conditions is not well understood and reliable estimates are difficult. This section describes how the stress/deformation analysis was done by using the Sigma/W numerical modelling software.

5.1 Stress/Deformation Modelling for the Phapvan Well-field

The well-field models were analyzed to calculate the subsidence due to the pumping of groundwater at the Phapvan and Maidich well-fields.

5.2 Boundary Conditions

The geometric mesh for the stress/deformation model was imported from the seepage analysis. This allows the modeller to define a problem that is based on a previously defined mesh. Therefore, the geometric mesh for the stress/displacement model is the same as the mesh of the seepage model as shown in Fig. 3. The following boundary conditions were assumed:

1. Displacements were zero in both the x- and y-directions along the bottom of the geometry (i.e., between the aquifer and the hard stratum),
2. Along the vertical boundary of the geometry (i.e., at both the left and right sides), the soil cannot move in the x-direction but is free to move in the y-direction, and
3. Along the exposed ground surface, the soil was free to move in both the x- and y-directions.

The material properties used in the stress-deformation analysis were determined from a combination of the laboratory test results and values published in geotechnical reports in Vietnam (Minh and Tam, 1993). The Young's modulus, E, of the silty clay and clayey silt with organics were calculated from consolidation test results. Young's modulus was computed using the equation given below:

[Eq.2]
$$E = \frac{(1+\mu)(1-2\mu)}{(1-\mu)m_v}$$

where:

m_v = coefficient of volume change,

μ = Poisson's ratio (assumed), and

E = Young's modulus.

Young's modulus for the sandy gravel layer was selected from Jumikis (1984). The Young's modulus values which best simulated results, and field measured values were chosen in stress-deformation analysis. The material properties used for the stress/deformation analysis model are summarized in Table 2. Poisson's ratio for the model was also assumed and presented in Table 2. A linear-elastic, drained stress analysis was performed for the subsidence problem.

6.0 RESULTS OF NUMERICAL MODELLING

The numerical simulation for Phapvan well-field was conducted for the period from 1988 to 2015. The numerical results of calculated subsidence along with the observed values at the Phapvan well-field for the period from 1988 to 1995 are presented in Fig. 5. The total settlement from the years of 1988 to 1995 is about 300 mm at the Phapvan well-field. The rate of settlement at the Phapvan well-field in 1995 was about 30 mm per year.

The future subsidence for the Phapvan well-field was predicted by assuming the proposed pumping schemes up to the year 2015. The numerical simulations showing the groundwater table drop for each year are presented in Table 3. The model predicted a total settlement of 743 mm at the Phapvan well-field from 1988 to the year 2015.

7.0 SUMMARY AND CONCLUSIONS

The findings from studying land subsidence due to the pumping of groundwater in the city of Hanoi are as follows:

1) Subsidence in the central and south-eastern part of the city of Hanoi (i.e., Phapvan well-field) were quite serious (i.e., subsidence rate is about 20 to 35 mm/year). When the soil stratum is composed of thick, compressible soils (e.g., peat, mud, clay and silt), there is a potential risk of subsidence.

2) The process of subsidence due to the pumping of groundwater and heaving of the land surface due to rise in the groundwater table or rainfall, is complicated. The prediction depends primarily greatly on the accuracy of the boundary conditions and the accuracy of the input data used in the models. The results obtained from the numerical modelling of the well-fields are close to the observed (or measured) results. The calibrated numerical modelling method can be used as a reasonable tool to estimate future subsidence due to further pumping.

3) Groundwater lowering can cause considerable land subsidence in Hanoi area. It is expected that settlements will be uneven because of non-homogenous soil conditions and because the coefficient of permeability varies both horizontally and vertically.

4) An intermediate step in the numerical estimation of subsidence is the prediction of the distribution of the pore-water pressures throughout the aquifer system. The model can then be calibrated by comparing the actual pore-water pressure distributions with the predictions based on the present pumping pattern. At present, little information exists on the piezometric conditions. The piezometric pressure conditions continue to decline in all areas of Hanoi.

5) The pattern of drawdown and subsidence based on numerical modelling, is reasonable. However, the magnitude of the predicted subsidence at a specific location may not be very accurate because of the lack of information on the soil geometry and soil properties. Simulations with variable well-field pumping schemes as a function of time can be ulitized to test where the maximum subsidence may occur. This information can be used in planning development in the city of Hanoi.

8.0 REFERENCES

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Table 1 Summary of calibrated and measured values used in the axi-symmetric seepage analysis at the Phapvan well-field

Material	Calibrated model (m/s)	Measured valuesof k (m/s)		
		Mean	Maximum	Minimum
Silty clay	3.0×10^{-7}	6.1×10^{-7}	3.4×10^{-6}	1.1×10^{-7}
Clayey silt	7.5×10^{-9}	8.7×10^{-9}	1.04×10^{-8}	3.4×10^{-9}
Sandy gravel	5.5×10^{-4}	6.6×10^{-4}	6.9×10^{-4}	5.8×10^{-4}

Table 2 Soil properties used in the stress/deformation analysis for the Phapvan well-field

Well-field	Material	Values in the models, E, kPa	Calculated values of E from consolidation tests, kPa			Poisson's ratio
			Mean	Maximum	Minimum	μ
Phapvan	Silty clay	1200	854	1405	813	0.33
	Clayey silt	3150	2177	3328	1985	0.33
	Sandy gravel	100000	-	-	-	0.29

Table 3 Summary of the settlement prediction at the Phapvan well-field for the period from 1996 to 2015

Year	1996	1997	1998	1999	2000	2001	2001	2003	2004	2005
Calculated Settlement (mm)	32	25	27	24	22	18	19	22	15	16

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Calculated Settlement (mm)	18	15	12	16	17	35	28	32	23	25

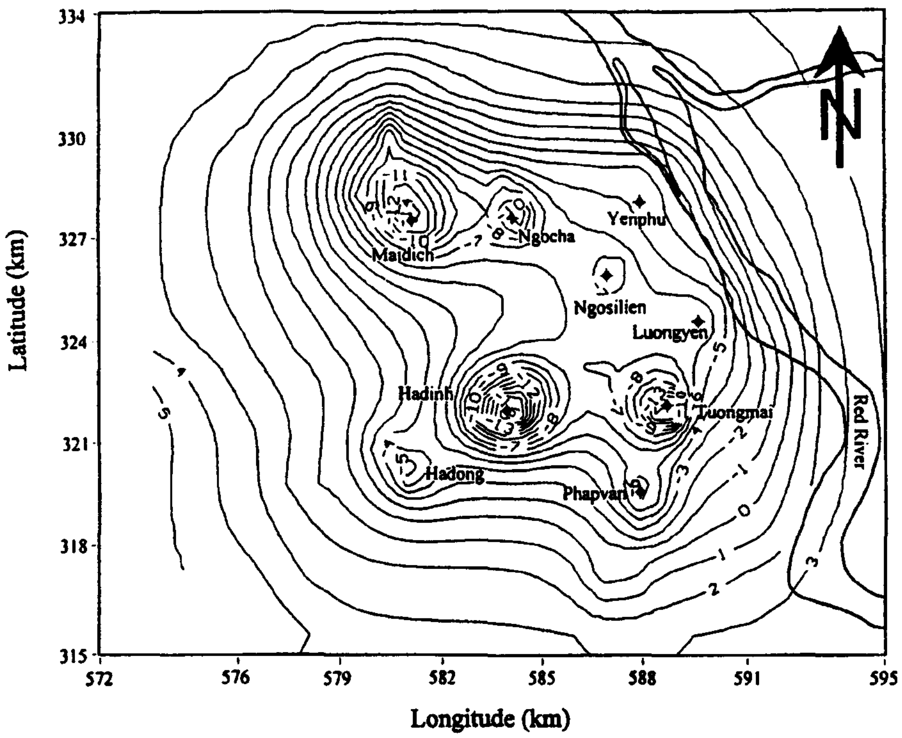

Figure 1. Contours map of the calculated heads (in metres) for the aquifer layer in 1990

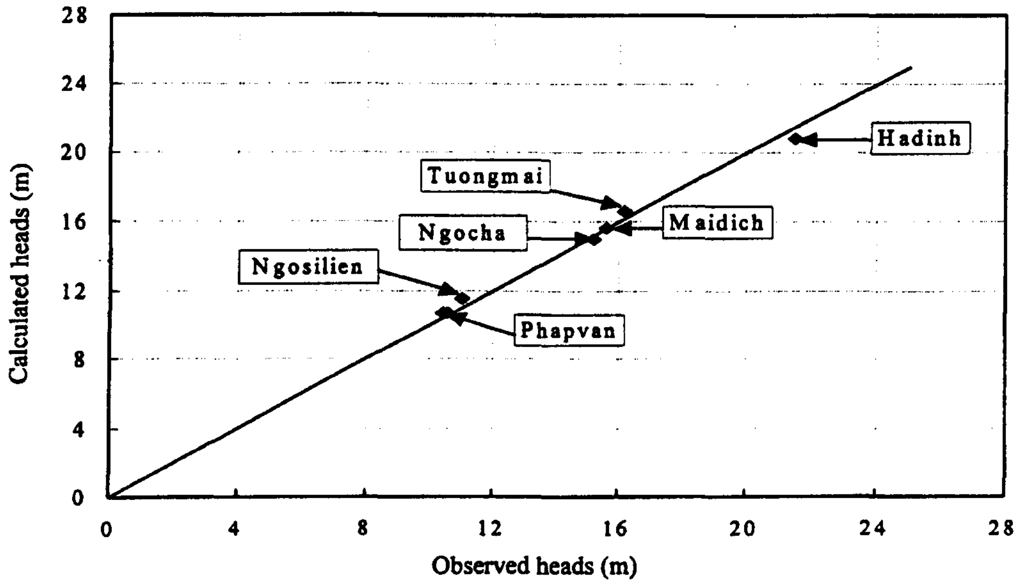

Figure 2. Simulated heads versus the measured heads for 1995 in the Hanoi city area

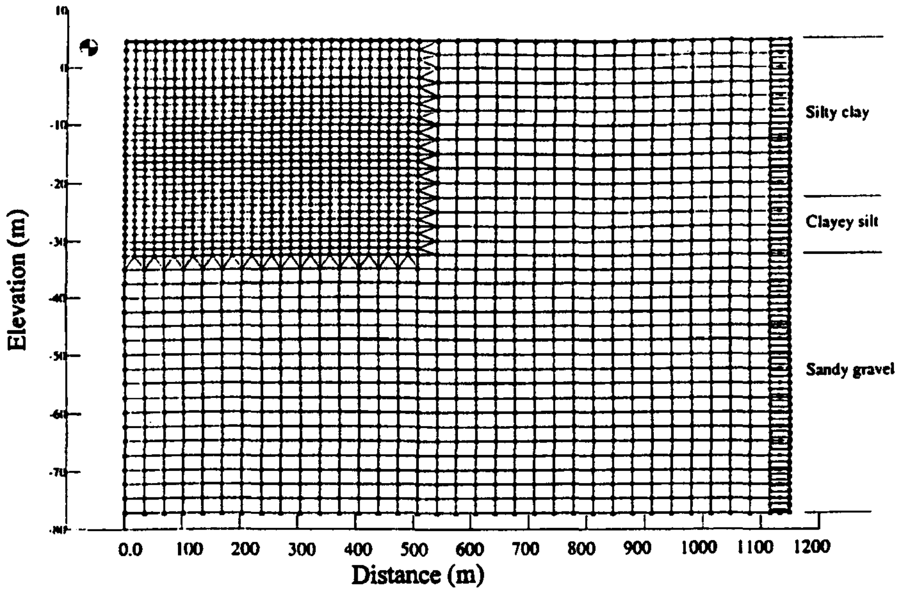

Figure 3. The geometric mesh along with boundary conditions for the axi-symetric seepage analysis at the Phapvan well-field

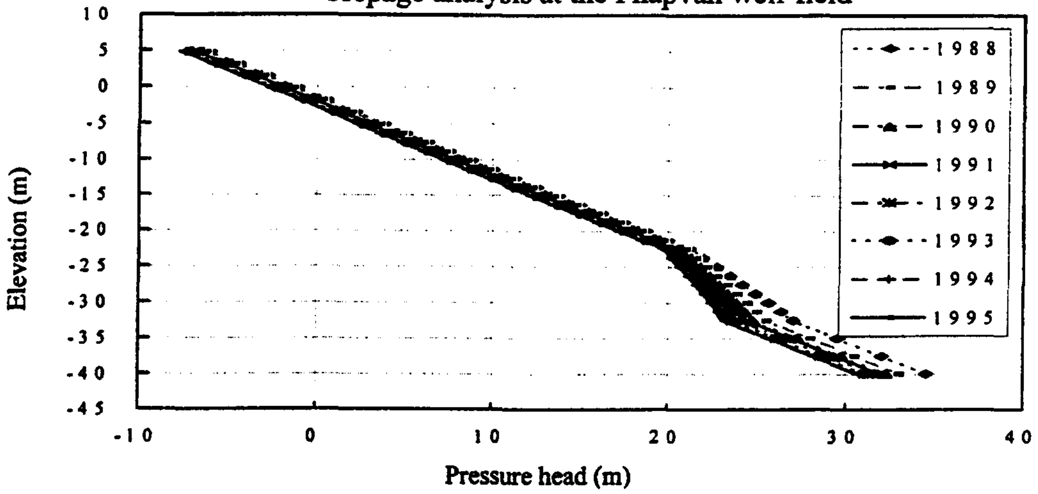

Figure 4. Pressure head versus elevation profiles for the period from 1988 to 1995 at Phapvan well-field

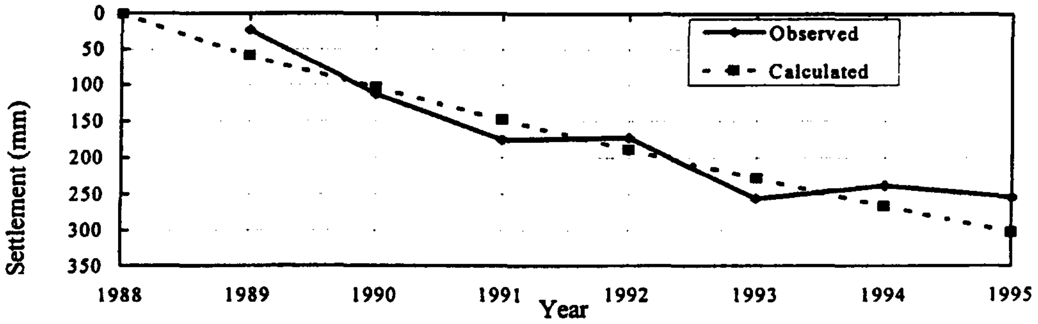

Figure 5. Calculated and observed subsidence at the Phapvan well-field for the period from 1988 to 1995