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MODELING OF GROUND SUBSIDENCE IN OIL FIELDS

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A b s t r a c t

A method of integrated analysis and prediction of ground subsidence in oil fields is being developed at the Canadian Centre for Geodetic Engineering. The method utilizes the in-situ data such as location and geometry of the oil reservoir, geology, pressure in oil wells, production data, and surface deformation monitoring results. The data is used in forward analysis of deformation analysis of the rock mass. The reservoir compaction and subsidence modeling is based on the functional relationship between production, change of pressure in underground oil reservoir and measured ground subsidence. As a first stage of the study, various methods of ground subsidence modeling have been implemented and compared in modeling the effects of oil extraction in oil fields along La Costa Oriental del Lago de Maracaibo (COLM) in Venezuela. A method of "nucleus strain", Knothe's influence function, and finite element method have been used in the comparison.

MODELOWANIE OSIADAŃ POWIERZCHNI NA POLACH NAFTOWYCH

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S ł o w a k l u c z o w e: pola naftowe, osiadanie, funkcja wpływów, metoda elementów skończonych.

S t r e s z c z e n i e

Metoda zintegrowanej analizy i przewidywania osiadania powierzchni górotworu wywołanego wydobyciem ropy naftowej została opracowana przez Kanadyjskie Centrum Geodezji Inżynieryjnej. Metoda ta jest oparta na wykorzystaniu takich informacji, jak geometria zbiornika roponośnego, budowa geologiczna górotworu, stan ciśnienia w otworach wiertniczych, dane wydobycia ropy naftowej oraz dane pomiarowe osiadania powierzchni górotworu. Dane te są wykorzystywane w modelowaniu osiadania powierzchni górotworu na podstawie obliczonej kompakcji zbiornika roponośnego. W analizie wykorzystano relacje między zmianami ciśnienia w zbiorniku, produkcji i pomierzonym osiadaniem powierzchni. Porównano trzy modele obliczania osiadania powierzchni, wykorzystując dane z eksploatacji pól naftowych w La Costa Oriental del Lago de Maracaibo (COLM) w Wenezueli. Modelami tymi były model "nucleus strain", metoda Knothego oraz metoda elementów skończonych.

Introduction

Ground subsidence due to withdrawal of underground fluids may produce catastrophic damages to the surface infrastructure and to the environment. Subsidence rates of several decimetres per year with the recorded accumulated subsidence reaching several metres are not uncommon in some parts of the world. For example:

– withdrawal of oil, gas and water in the Wilmington oil field, in Long Beach, California, produced land subsidence of 8.8 m between 1932 and 1965 (Kosloff et al. 1980),
– extraction of underground water for irrigation purposes in the San Joaquin Valley in California, reached 9.0 m between 1935 and 1977 (Poland 1984),
– extraction of underground water in the Wairakei geothermal field in New Zealand experienced up to 14 m of subsidence between1950 and 1997 (Allis 2000),
– withdrawal of oil in Lost Hills oil field in California has recorded subsidence rates of up to 40 cm/year (Fielding et al. 1998),
– withdrawal of oil in the Ekofisk oil field in the Northern Sea has reached subsidence 8.5 m between mid 70s and 2004 (Musharraf et al. 1995),
– withdrawal of oil in oil fields along the east coast of Maracaibo Lake (Murria 1991) in Venezuela, where subsidence has reached 7.0 m between 1926 and 2004.

The recently developed closed-loop reservoir management approach for the petroleum industry, known as the Integrated Reservoir Optimization (IRO) process (Beamer et al. 1998) is based on more complete understanding of reservoir characteristics and performance. The IRO process has four stages: 1) Reservoir characterization; 2) Development planning; 3) Field implementation; and 4) Reservoir monitoring and control. The last stage, i.e. modeling, monitoring, and controlling of production is fundamental for better understanding of processes and optimization of existing and future oil production. Development of a methodology for predicting the effects of oil production on the surface, is crucial for planning a safe and economical production particularly in the areas, where surface subsidence may have catastrophic effects. The aforementioned oil fields in Venezuela are a notable example. Due to the oil withdrawal along La Costa Oriental del Lago Maracaibo (COLM) most of the inland area with thousands of inhabitants and the production infrastructure is already several metres below the lake level. Over 50 km of earth dykes protect the area from flooding Figure 1 shows a portion of COLM area and the dyke. The dykes must be continuously upgraded due to the progressing subsidence (MURRIA 1991). The oil production must be carefully planned to induce as little deformation to the dykes as possible.

Several empirical and deterministic methods are available for predicting ground subsidence in the areas of mining solid minerals (CHRZANOWSKI et al. 1998). Modeling and prediction of ground subsidence due to oil withdrawal is, however, more complex. The boundary and geometry of the productive zone of the reservoir as well as the amount of the actual compaction are difficult to determine.

Development of a methodology for predicting ground subsidence in oil fields is one of the recent research projects carried out at the Canadian Centre for Geodetic Engineering. The development of the prediction model must be preceded by selecting and/or developing the optimal method for modeling ground subsidence and developing functional relationships between the ground subsidence, volume of production, change in reservoir pressure, and the resulting compaction of the reservoir material. In this paper the authors give preliminary results of comparing various methods of ground subsidence modeling in Lagunillas, the largest oil field in the COLM area. The following methods have been used in the comparison:

– deterministic method using the finite element method (FEM),
– nucleus of strain method (GEERSTMA 1973), and
– Knothe's method (KNOTHE 1984, KRATZSCH 1983) adapted from modeling ground subsidence in mining areas.

Subsidence as a function of reservoir compaction

Due to withdrawal of oil or any other fluid, the weight of sediments above the producing reservoir is supported partially by the rock matrix and partially by the fluid pressure in the rock pores (BRUNO and BOVBERG 1992). When fluids are extracted from an underground reservoir, a decline in pore pressure is produced, resulting in shrinkage or compaction of the reservoir. Accurate modeling of depletion-induced subsidence requires an understanding of the mechanical behavior of the reservoir and surrounding rock mass (HETTEMA et al. 2002). The amount of the subsidence depends on the extraction method and its volume, the extent and depth of the extraction zone, the compaction of the reservoir material, and on the type of overburden material (Martin and Serdengecti 1984).

In case of lateral dimensions of a reservoir being large compared to its height (thickness), the reservoir changes its dimensions mainly in the vertical plane. The decline in pressure in the reservoir produces a change in the stress field of surrounding rock mass that generates the surface subsidence. The total reduction of the height of the reservoir (compaction C) can be obtained from (Geertsma 1973):

$$C = \int_0^h C_m(z)\ \Delta p(z)\ dz \tag{1}$$

where:

$C_m(z)$ uniaxial compaction coefficient in (kPa^{-1})
h original reservoir thickness in (m)
$\Delta p(z)$ change in pore pressure of the reservoir in (kPa).

In case of constant parameters of reservoir, the compaction is given:

$$C = C_m\ \Delta p\ h \tag{1a}$$

The compaction is dependent on the reduction of the pore pressure in the reservoir, and is a function of mobility, solubility, density, and compressibility of the pore fluids, and boundary conditions such as, for example, faults.

The compaction coefficient C_m is a very important factor influencing the compaction and is dependent on rock type, degree of cementation, porosity, and depth of the reservoir. For an elastic isotropic material, the uniaxial compaction coefficient is defined as (Bruno 2001):

$$C_m = C_b \frac{1+\upsilon}{3(1-\upsilon)} \tag{2}$$

where:

C_b bulk compressibility in (kPa^{-1}),
υ Poisson's ratio for the material.

Bulk compressibility is defined as the change in bulk volume per unit of bulk volume dV_b, as a function of the change of vertical stress $d\sigma_z$ (Donaldson 1995):

$$C_b = \frac{1}{V_b}\frac{dV_b}{d\sigma_z} \tag{3}$$

Since most of the compaction occurs in the vertical direction, the bulk compressibility can be determined as

$$C_b = \frac{1}{h}\frac{dh}{d\sigma_z} \tag{4}$$

The uniaxial compaction coefficient C_m is then related to the reduction in thickness of the reservoir per unit of stress increase in the vertical direction under a constant loading rate and with radial deformation being prevented (van HASSELT 1992). The uniaxial compaction coefficient C_m varies between 0.3 x 10^{-7} kPa^{-1} for rock and 20 to 40 x 10^{-7} kPa^{-1} for loose sands (GEERTSMA 1973). SCHENK and PUIG (1982) developed an empirical formula for the determination of C_b for oil fields in the COLM area in Venezuela as:

$$C_b = \frac{0.08}{Pe} \tag{5}$$

where Pe is the effective pressure, which is determined as a difference between the overburden pressure and the average fluid pressure of the reservoir.

Estimation of the reservoir compaction when average values of C_m, Δp and h are used gives a constant value of compaction for the whole reservoir, which is unlikely to happen in reality. Reservoirs are usually of variable thickness and the change of pressure varies throughout the reservoir depending on many factors, such as reservoir shape, initial pressure distribution, reservoir porosity and permeability, rate of production, rate of injection, fluid properties, etc. Reservoir simulators that make use of the equations governing the flow of fluids through porous media can determine the change of pressure field of a reservoir needed for the determination of compaction. An approximation of the change of pressure distribution throughout the reservoir can also be obtained from pressure history observations at production or exploratory wells, or both, spatially distributed.

Lagunillas oil field in venezuela

Venezuela has the western hemisphere's largest oil reserves of 77 billion barrels in four major sedimentary basins: Eastern, Western, Barinas-Apure (where most oil production occurs), and the largely unexplored Northern basin. There are a total of 360 fields, representing more then 17 300 identified reservoirs (SCHLUMBERGER 1997). In the eastern basin the main active oil fields are located along the East Coast of Lake Maracaibo (known as COLM area). There are three major oil fields: Tia Juana, Lagunillas, and Bachaquero extending from inland into the lake. Among them, Lagunillas field is the largest with the total area of 163 km^2 and with over 1500 active wells. The area of COLM is divided into production blocks 1.4 km x 1.2 km (Murria 1991) containing 36 wells with one gathering station per block (Finol and Sancevic 1997).

Data from the inland portion of Lagunillas has been selected for the preliminary testing of various methods for modeling ground subsidence. Oil is extracted from two, almost horizontal, reservoirs at two different levels: upper reservoir at the average depth $H_U = 674$ m and average thickness $h_U = 84$ m and lower reservoir at $H_L = 851$ m and $h_L = 37$ m. Figure 2 shows the outlines of the inland portion of the reservoirs. Monitoring of ground subsidence has been conducted on a bi-annual basis since 1926 using leveling of high precision (Leal 1989). In 1988, GPS was added to the monitoring scheme to gain information on the horizontal movements (Chrzanowski et al. 1988) and to connect the levelling network to far away reference points. The rate of subsidence in Lagunillas reaches 20 cm/*y*. In 2004, the maximum accumulated subsidence reached 7.0 m. In order to protect the inland part from flooding by the lake, a system of protective earth dykes is maintained and continuously upgraded.

Modeling of subsidence

Available Data

A period of four years between 1996 and 2000 has been selected for the preliminary testing of three methods of modeling based on: Knothe's influence function (Knothe 1984, Kratsch 1983), Nucleus Strain approach (Geertsma 1973) and deterministic modeling using finite element method (FEM) (Szostak-Chrzanowski et al. 2005).

The following data has been obtained from PDVSA oil company to conduct the preliminary study:
– results of bi-annual leveling,
– CAD files showing boundaries, depth, and thickness of reservoirs,
– locations of oil wells in the inland area,
– production history data for the inland area,
– observed pressures in individual oil wells (for upper and lower reservoirs).

In order to perform a preliminary analysis on the global correlation between production, change in pressure, compaction, and observed subsidence in the whole area, the data was averaged and generalized. It was more practical to

Fig. 1. Protective earth dyke

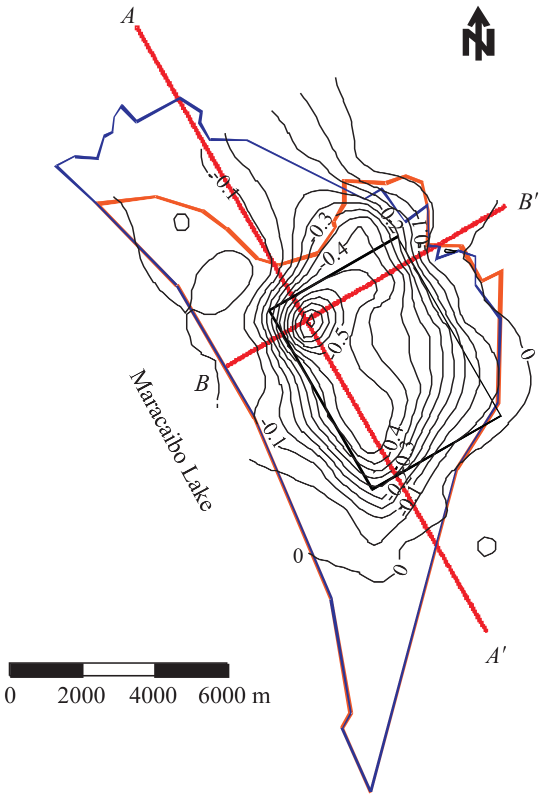

Fig. 2. Outline of the inland reservoir

perform a global study for the whole field rather than separate studies at each well. The compaction was assumed to be in soft clay layers in and adjoining the producing sand layers. Based on van der Knaap and van der Vlis (1967), uniform compaction behavior over the area was assumed.

The productive area of the oil reservoir was identified (rectangular area in Fig.1) based on the observed pressure changes. To simplify the analysis, the upper and lower reservoirs in the productive area were combined into one reservoir of an average thickness of 240 m (Fig. 3). The overburden material (unconsolidated sand) was accepted as homogenous and anisotropic. On the basis of the pressures observed in the wells, the productive area has been divided into two zones. The averaged pressure in Zone 1 was obtained as equal to –1000 kPa and in Zone 2 equal to –500 kPa (Fig. 2).

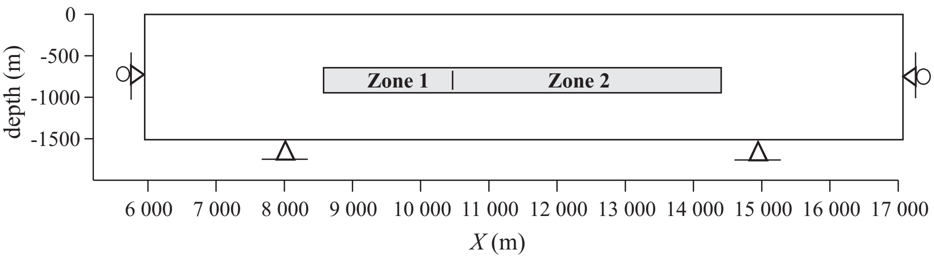

Fig. 3. Model of the combined upper/lower reservoir along A-A’ cross-section

Modeling of Subsidence using Knothe’s Influence Function

Several formulations of influence functions have been postulated in mining subsidence studies by different authors. Among these, Knothe’s influence function (Knothe 1953) is one of the most popular in mining industry of Central Europe, particularly in coal mining. Knothe’s influence function has the form (Kratzsch 1983):

$$k_z = \frac{e^{\left(-\frac{\pi r^2}{R^2}\right)}}{R^2} \tag{6}$$

where:

r – horizontal distance between the reservoir element and the surface point of subsidence,

R – radius of critical area (a minimum area, which produces maximum possible subsidence).

By integrating influence of elementary elements dA over the productive area A and by replacing height of mining excavations by the compaction C at each element, one may adapt Knothe's theory to the calculation of subsidence in the area of fluid withdrawal from:

$$s = -a\int_A C k_z dA \qquad (7)$$

where:

a – spreading factor.

The spreading factor is a measure of the relationship between maximum subsidence and maximum compaction and is a positive number smaller than 1. For shallow reservoirs covering a large area, maximum subsidence will be very close to maximum compaction and the subsidence spreading factor will be approximately $a = 1$ (MARTIN and SERDENGECTI 1984).

The subsidence spreading factor 'a' and the value of R must be determined empirically from data of observed subsidence in the given area. For Lagunillas productive area, the critical radius of influence for Knothe's model was found as the horizontal distance from the edges of the productive zone of the reservoir to the point of maximum subsidence resulting in an average value of $R = 1100$ m. The compaction C at each element of the numerical solution of the integral in equation (7) was calculated from equations (1), (2) and (5) accepting the value of Poisson ratio $\nu = 0.3$. The value of 'a' was determined at the point of maximum subsidence as the ratio of s/C = $a = 0.69$.

Figure 4 shows the plot of the calculated subsidence along the profile AA' for the period 1996–2000.

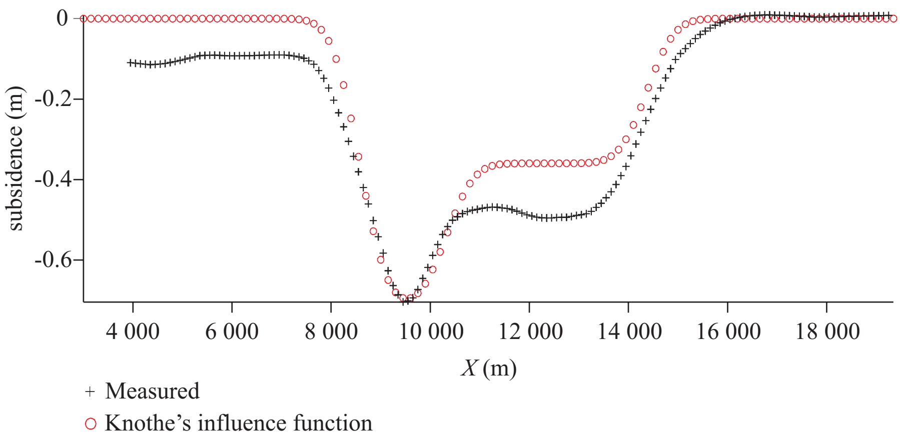

Fig. 4. Observed and calculated subsidence using Knothe's influence function

Modeling of Subsidence Using the "Nucleus of Strain" Approach

In case of fluid withdrawal, a technique called "nucleus of strain" was developed by Geertsma (1973) to calculate surface subsidence. In this technique, the volumetric strain at a point in reservoir, caused by a local reduction in pore pressure is treated as a center of compression in an elastic half-space that produces a displacement field at the surface. By integrating the contribution of all the compression points over the reservoir, the resulting surface subsidence caused by the decline of the reservoir pressure can be calculated. The 'nucleus of strain' model assumes linear rock behavior with both rock and reservoir being homogeneus and having the same material properties. By integrating (using a numerical solution) the contribution of all the compression points over the reservoir, the resulting surface subsidence can be calculated from (Bruno 1992):

$$s = -\frac{1-\upsilon}{\pi} \int_A C_m \frac{H}{\left[r^2 + H^2\right]^{3/2}} \Delta p \, dA \tag{8}$$

where:

C_m – compaction coefficient of a reservoir element dA in (kPa^{-1}),
H – depth of the reservoir in (m),
r – horizontal distance between the reservoir element and the point of subsidence on the surface (m).

As in modeling with Knothe's influence function, the calculated displacements were obtained from a numerical solution of the integral in equation (8). The value of compaction coefficient Cm was calculated using equation 2 and equation 5

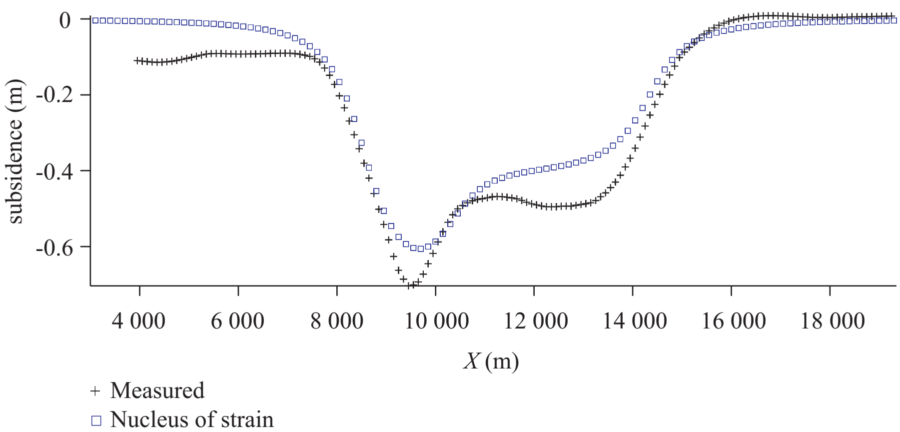

Fig. 5. Observed and modeled subsidence using the Nucleus of Strain method

and was 38 x 10^{-7} kPa^{-1}. The value of the Poisson ration was accepted as $\nu = 0.3$. Figure 5 shows a comparison between the observed and modeled subsidence. In order to get the agreement at the point of the maximum subsidence between the observed and calculated subsidence, the empirical formula given in equation 5 should be replaced by

$$C_b = \frac{0.06}{Pe} \tag{9}$$

This will require additional investigation.

It can be seen that the nucleus of strain and the influence function approaches are similar in the sense that they both integrate the contribution of elementary extraction elements to calculate surface subsidence.

Modeling of subsidence using FEM

The Finite Element Method (FEM) has become one of the most usable among deterministic methods in modeling of ground subsidence. The deterministic methods require reliable information on the in-situ properties of rocks, initial stresses, tectonics of the area, method of extraction, and history of extraction. In case of rock and soil materials, the in-situ geomechanical properties should significantly differ from the laboratory values (BIENIAWSKI 1984) mainly due to the scale factor (JING 2003). This must be taken under consideration when using laboratory data in deterministic modeling of deformations. The FEM solution allows to model non-homogenous non-isotropic materials. In case of a presence of tectonic stresses in rock mass, the values of stresses may be included in the analysis.

In order to perform the finite element analysis the following steps must be taken:

1) selection of the model for the analysis (geometry, loading and boundary conditions),
2) selection of the material model (e.g., linear elastic, non linear),
3) selection of geomechnical parameters of the materials.

In addition, the method of oil withdrawal and tectonics of the area should be considered.

The preliminary two-dimensional FEM analysis was performed for the AA' cross-section shown in Figure 2. The geometry of the model followed Figure 3. The initial state of stress was investigated. No tectonic stresses were included in the analysis, though it is known that the Lagunillas area is prone to seismic events. The given changes in the pressures were used as the loading condition. The value of Poisson ratio was taken as in other models, $\nu = 0.3$, while the value of Young modulus $E = 183$ MPa was obtained through calibration by taking the calculated subsidence at the point of maximum subsidence equal to the observed value. Figure 6 shows comparison between the observed and modeled subsidence.

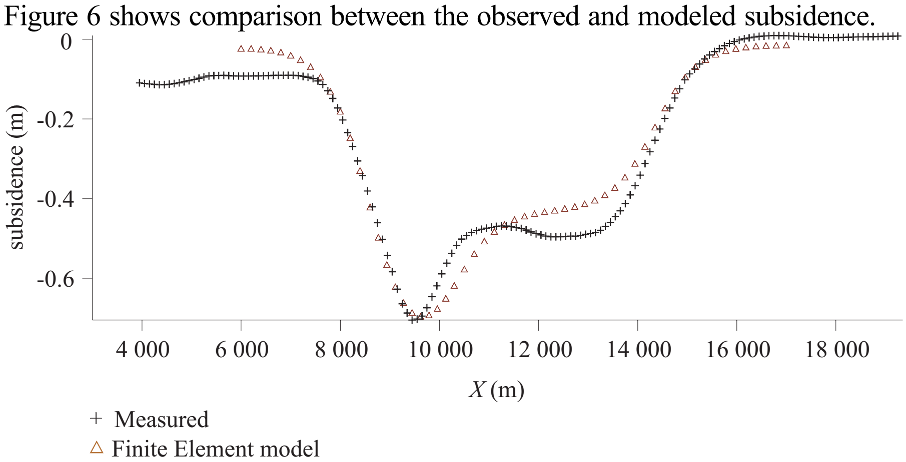

Fig. 6. Observed and modeled subsidence using FEM

Conclusions

The all three investigated methods of modeling ground subsidence gave reasonable good agreement with the observed subsidence. This indicates that the preliminary assumption on the overburden rock being homogenous and continuous in the investigated area is correct. One could calibrate the value of Young modulus, E for the rock mass and the value of the compressibility coefficient Cb. for their future application in developing a prediction model. These values will require verification by performing more detailed analysis for various periods of time using the historical observation data. To better understand the phenomena of relation of the compaction process and subsidence for more complicated reservoir geometries and loading conditions, FEM is more suitable than influence function and "nucleus strain" methods.

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