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TIDAL PRESSURE RESPONSE AS A RESERVOIR ENGINEERING TOOL

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ABSTRACT

Fluid pressure oscillations resulting from tidal strain reflect hydrologic and elastic properties of a reservoir. Precise measurement and interpretation of these pressure fluctuations has the potential of being a useful quantitative reservoir engineering tool. Interpretations of reservoir response to tides have been to date of a qualitative nature. This is primarily due to the lack of resolving power of the spectral analysis techniques applied in the data interpretation. We have developed a procedure, based on the statistical nature of the noise in the signal, that overcomes most of these problems. The method quantifies the spectral resolution in terms of an absolute confidence level in both amplitude and phase of the spectral estimate. Analysis of one week of data from a well in the Salton Sea KGRA is presented.

INTRODUCTION

The relatively recent development of extremely sensitive pressure sensing devices, combined with simple and proven modifications to these devices to allow for extended downhole time in corrosive and hot brines, has opened the possibility of using tidally driven fluid pressure oscillations as pressure transient sources in geothermal reservoir engineering. The procedure involved to extract information on reservoir properties is similar to that of conventional well pumping tests: (1) a well-reservoir mathematical model is constructed based on assumed elastic and hydrologic constitutive relations in order to obtain the theoretical pressure response of the reservoir to the tidal strain and (2), a comparison of the observed with the theoretical response to obtain the reservoir parameters. Several simple well-reservoir models have been presented in the literature (Bredehoeft, 1967; Bodvarrson, 1970; Arditty, 1978). To date, conclusions drawn from field application based on existing models are for the most part qualitative (Bredehoeft, 1967; Arditty, 1978). This derives, to a significant degree, from the rather complicated nature of the driving signal, the fact that the tidal pressure response can easily be of the same magnitude as naturally occurring or culturally induced noise, and the instrument resolution. Digital spectral analysis techniques that have usually been applied to the analysis of tidally excited signals do not extract all of the available information from the data, fail to place on the spectral estimates a confidence interval that reflects the true noise spectrum, or both of these. Application of the Fast Fourier Transform (FFT) (Arditty, 1978), in addition to the above problems, can indeed distort the spectral estimates unless a long time record of the signal is processed. Munk and Hasselman (1964) addressed the problem of resolving, in an arbitrarily long data sample, two closely spaced spectral lines in noise. Although this work lays bare some of the problems associated with analysis of the tidal spectrum, it does not generalize to the degree necessary for practical application. The following outlines a general method of analysis we have developed and gives as an example an application to field data taken in the Salton Sea KGRA.

ANALYSIS OF SIGNALS WITH TIDAL ORIGIN

The tidal spectrum consists of an infinite but countable set of discrete frequencies related to the orbital periods of the earth about the sun, the moon about the earth, and the earth's rotation. Fortunately, 95% of the tidal gravitational potential is represented by a set of five spectral lines: two diurnal lines (O_1 and K_1) and three semidiurnal lines (N_2, M_2, and S_2) (Melchior, 1964). The periods of these lines are given in Table 1. The multiplet groups (eg. diurnal, semidiurnal, and terdiurnal) are spaced on the order of 0.04 hr^{-1} from one another and individual lines within these groups are spaced on the order of 0.002 hr^{-1} or less from one another. Melchior (1978) gives a comprehensive description of the tidal spectrum.

A spectral estimate of the line $\omega = \omega_k$ is made according to

$$F(\omega_k) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{i\omega_k t} g(t)h(t)dt \qquad (1)$$

where $g(t)h(t)$ is the measured signal consisting of the true tidal signal $r(t)h(t)$ superimposed on random noise $n(t)h(t)$. For a given data length L, $h(t)$ is unity on the interval $[-L/2, L/2]$ and is zero elsewhere. Equation (1) can be recast, using the convolution theorem for Fourier integrals, as

$$F(\omega_k) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} G(\omega)H(\omega_k-\omega)\, d\omega \tag{2}$$

where $G(\omega) = R(\omega) + N(\omega)$ is the spectrum of the signal plus noise and $H(\omega)$ is a sinc function kernel. In this form, it is evident that the calculated spectral estimate $F(\omega_k)$ consists of a weighted sum over $G(\omega)$. Only for very long data lengths such that $\Delta\omega L \gg 1$ will the kernel approach a delta-like function and $F(\omega_k)$ be a good estimate of $G(\omega_k)$. $\Delta\omega$ is on the order of the line spacing in the above constraint suggesting that L must be on the order of months. For short data lengths, a month or less, the above integral equation must be solved (deconvolved) for $G(\omega_k)$. Since the tidal spectrum is discrete ($\omega = \omega_k$, k = 1, 2, ..,M), equation (2) can be recast into a set of 2M coupled equations with 2M unknowns (M estimates of Re G and M estimates of Im G). This will yield the values of $G(\omega_k)$ which best represent $R(\omega_k)$ in the least squares sense. If, in addition to being random, the noise is assumed to be a stationary ergodic time series, an expression for the variance-covariance matrix for each spectral line estimate $G(\omega_k)$ in terms of the noise power spectrum can be derived using the method of ensemble averaging. The diagonal elements of this matrix (variance) reflect the uncertainty in the real and imaginary parts of the spectral estimates and the off diagonal elements (covariance) reflect the correlation between the real and imaginary parts of the spectral estimates. The covariance term is zero for white noise. The variance-covariance matrix is used to delineate regions in the amplitude-phase plane within which, to some given probability, the true spectral estimate will be constrained. It may be possible to propagate this information through a well-reservoir model to obtain confidence bounds on the computed reservoir parameters.

TABLE 1

SYMBOL	MULTIPLET	PERIOD (HRS)	ORIGIN (L = LUNAR, S = SOLAR)
O_1	DIURNAL	25.819341	L PRINCIPLE LUNAR WAVE
K_1	"	23.934469	L & S DECLINATIONAL WAVE
N_2	SEMIDIURNAL	12.658348	L MAJOR ELLIPTIC WAVE OF M_2
M_2	"	12.420601	L PRINCIPLE WAVE
S_2	"	12.000000	S PRINCIPLE WAVE
M_3	TERDIURNAL	8.280401	L PRINCIPLE WAVE

The analysis procedure outlined above has been extensively tested using simulated data with varying levels of superimposed noise and varying lengths of data.

APPLICATION OF METHOD TO FIELD DATA

The method has been applied to approximately one week of raw (unfiltered) data taken between 0730, 5/23/78 and 1000, 5/30/78 at Elmore 3, a well located in the Salton Sea KGRA. The well liner is slotted in the interval 2007'-2505' and cores taken from this interval vary from silty shales to loose and very coarse sand. Conventional pressure build-up and drillstem tests in Magmamax 1, a well within 2 miles of Elmore 3, yield a value of approximately 150 md for the permeable sands at this depth (Morse, 1979). The well had been shut in for some months and the nearest well undergoing flow was more than one mile away. A Paroscientific Quartz pressure gauge, modified for extended downhole use in a hot and corrosive environment (Morse and Owen, 1978) was suspended at a depth of 150'. It is noted here that this instrument has functioned without interruption for downhole periods in excess of several months at the SSKGRA. Figure 1 shows the raw data after having been corrected for an assumed quadratic instrument drift. The data was sampled six times an hour. Shown also in Figure 1 is the theoretical gravity tidal perturbation (Longman, 1959). The polarity of the gravity has been reversed here for easier visual comparison with the pressure data. The analysis of this data allowed for the five tidal lines referred to earlier plus the terdiurnal line M_3 (see Table 1) and assumed that the noise present in the signal was white for computational ease. The best estimates of the six lines in the tidal pressure response, with associated 50% confidence intervals, are shown in Figure 2. Except for the N_2 line, bounds on both amplitude and phase are obtained at the 50% confidence level for all spectral estimates. An upper bound on the amplitude of the N_2 tide at this confidence level is obtained although the phase of this line is not resolved. Furthermore, at this confidence level, K_1 and O_1 in the diurnal multiplet and M_2 and S_2 in the semidiurnal multiplet are resolved as separate and distinct lines. An FFT analysis (see Figure 3) of the same data delineated the three multiplet groups but failed to resolve amplitude and phase of individual lines within each group.

An identical analysis was done on the theoretical gravity over the same time period to determine if, within a given confidence, a frequency dependent amplitude or phase response of the reservoir to the tidal strain could be detected. Existing well-reservoir models (Bodvarsson, 1970; Arditty, 1978) indicate the possibility for this reservoir behavior. The well pressure data not only reflects a response to tidal strain but also to barometric and thermal fluctuations that can have significant energy in the spectral window corresponding to the solar day. To eliminate, or at least minimize, these effects in our comparison of the gravity with the pressure data, we normalized the spectral estimates to the purely lunar tide O_1 with respect to both amplitude and phase. Figure 4 shows the comparison of the normalized results with 50% confidence levels on the pressure estimates and 90% confidence levels on the gravity. If the tidal response of the reservoir had been independent of frequency, the magnitude of the vectors would have been zero. From these results, there is a definite indication (at better than a 50% confidence) that the response is indeed frequency dependent. The pressure response of the reservoir to the semidiurnal tides M_2 and S_2 lags the semidiurnal gravitational perturbation in phase. Furthermore, there is a weak indication of a frequency dependent amplitude response although the confidence in this conclusion, based on one week of unfiltered dàta, is significatnly less than 50%. Finally, it is noted that the lunisolar tide K_1 exhibits a large excursion relative to the lunar tide O_1. As suggested earlier, this is most likely due to thermal and barometric effects and indicates the necessity of isolating temperature sensitive equipment, taking pressure measurements at a sufficient depth to avoid contamination by surface temperature variations, and correcting the data for barometric effects prior to analysis.

CONCLUSION

The results of our analysis of a short time record of pressure response at Elmore 3 suggests that the method of tidal spectral analysis presented here will have the potential for providing constraints on amplitude and phase response of a reservoir necessary to estimate, to a useful degree of certainty, reservoir hydrologic properties. These constraints will also be necessary to verify the applicability of existing well-reservoir models or to indicate changes to existing models required to account for observed reservoir response. The method is applicable to the analysis of anv signal of tidal origin and will be useful in the interpretation of tilt-meter and direct strain data in addition to tidal pressure fluctuations. Evaluation of the tidal approach to reservoir engineering is currently underway at Lawrence Livermore Laboratory. A critical comparison of this method with the more conventional well pumping approach will be made on data taken at the SSKGRA and at Raft River, Idaho.

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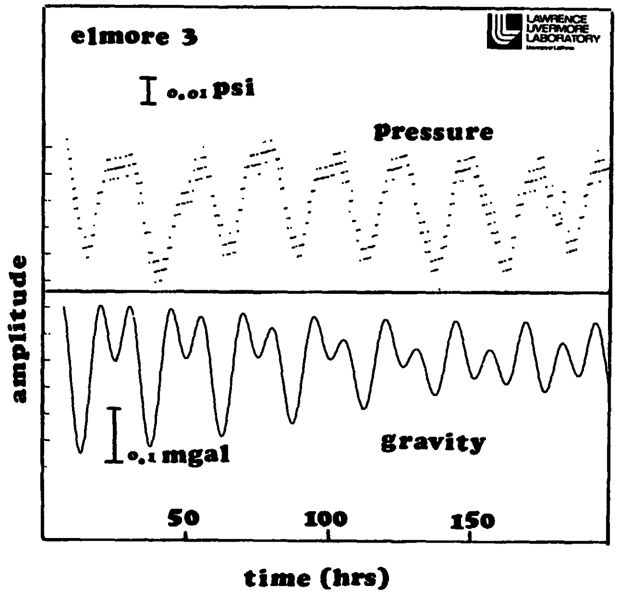

Figure 1. Measured tidal pressure response and theoretical tidal gravity perturbation at Elmore 3, SSKGRA.

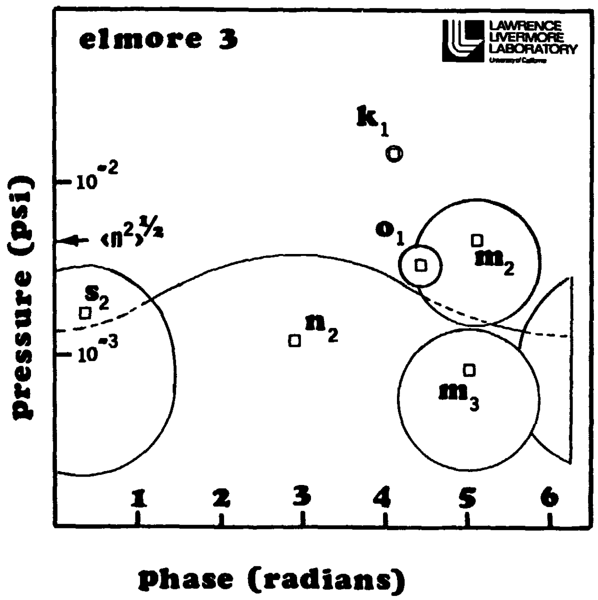

Figure 2. Spectral estimates of six lines of the tidal spectrum in the reservoir pressure response. Ellipses indicate 50% confidence levels. Rms nois level given by arrow.

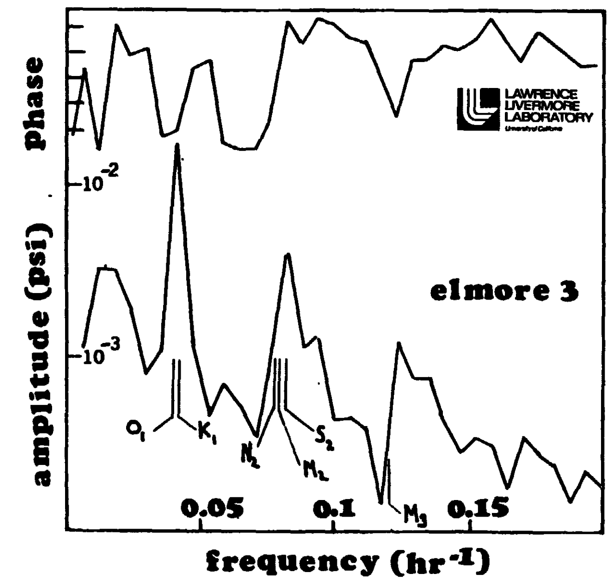

Figure 3. FFT analysis of one week of data from Elmore 3. Locations of the six spectral lines are given for reference.

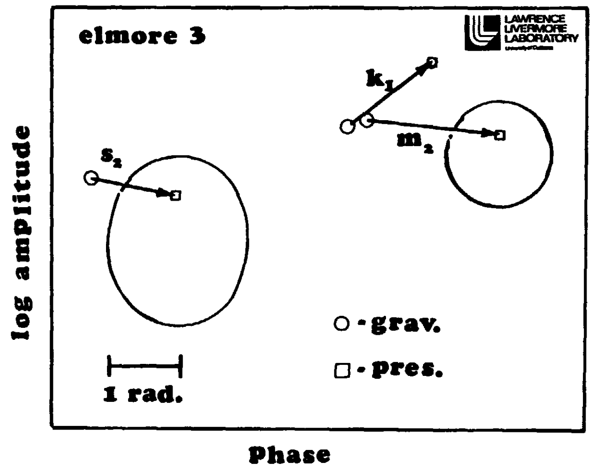

Figure 4. Normalized spectral estimates of k_1, M_2, and S_2 relative to the lunar tide O_1. Vectors indicate pressure response of reservoir to tidal strain.