Polyaxial Compaction of Depleted Rocks

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Abstract- This study examined vertical compaction of depleted reservoirs in a new way. From Hooke`s laws of elasticity, we generated polyaxial compactions in the rock by applying the Lagrange averaging technique, which gave a result for the stress-path parameters in the maximum horizontal stress direction. The formulation considered the pore pressure depletion in the reservoir. In addition, we provided a monograph, which can serve as a quick chart for reading up vertical compactions in the reservoir considered. Compaction of depleted rock is important, especially in reservoir geomechanics, as millions of US dollars are required in solving issues related to them. Engineers have used uniaxial compaction, in the vertical direction, to model surface subsidence and construct platforms for offshore drilling, but there are issues when using such compaction. The systems of reservoir stress are orthogonal in nature, vertical and lateral stresses exist at the subsurface, and the intermediate principal stress plays a role in a tectonic region. Thus, it is important to carry out a study of this magnitude. From the results, we find that, in normal stress regime, there is a significant difference between results of polyaxial compaction and uniaxial compaction at shallow depths. The difference diminishes to zero at much deeper depths, as the rock`s Poisson ratio approaches 0.5. The distribution of this Difference with Poisson`s ratio follows a near parabolic trend or a bell shape. In addition, the distribution varies with reservoir aspect ratio with a trend reversal.

Index Terms- Stress path parameters, Lagrange interpolation, depleted rocks, polyaxial compaction, uniaxial compaction.

I. Introduction

Rock compaction and surface subsidence are important phenomena in the study of the geomechanical behavior of depleted reservoirs. Rock compaction results from the increasing load of sediments deposited in a basin, ([1], [2], [3]), of which the primary effect is to reduce porosity, as pore space tends to close up in the process. When compaction occurs in a formation, the ground level must subside to maintain equilibrium, depending on the stiffness of the rock. Most drilling activities are in shale or clay formations, [4] that are susceptible to compaction because of plasticity and the tendency of releasing adsorbed water. The large-scale consequence of compaction and the corresponding subsidence are operational problems including surface flooding and onshore/offshore platform safety concerns [5]. Flooding can destroy natural habitat and make urban settlement unbearable. Platform safety concerns in the offshore environment can be detrimental to lives and property. The resulting surface subsidence can affect wellbore casing integrity. In petroleum geomechanics, these effects can reach up to millions of US dollars when solved. Particularly, platform jack-up requirement needed to solve the subsidence in the Ekofisk field of 1984 was at a cost of US $1MMM, [6].

The application of the theory of compaction, like the undercompaction theory, in predicting pore pressure is important. One problem is that such theory employs uniaxial compaction without considering the effect of 3D compaction, otherwise called polyaxial compaction. The overburden load together with the laterally compressing forces (or tectonic forces of the earth) acting on the formation can put the rock in the latter compaction state. At the subsurface, *in situ* stresses are orthogonal ([7] page 51, [8], [9] [10]). Stress changes are also orthogonal. For the uniaxial compaction, the stress regime is taken as normal with the maximum principal stress as the vertical stress and the minimum principal stress as the horizontal stresses. Here, the intermediate stress bears equal magnitude as the minimum stress.

In a tectonic zone, the intermediate stress can be very active ([11], [12]). Therefore, it is important to consider whether polyaxial compaction of rocks yields similar results as uniaxial compaction or not. The stress state for a significant number of formations is distributed such that the vertical stress is the maximum principal stress while the horizontal stresses can have the intermediate and minimum principal stresses.

Depleted rocks are those having pore pressure reduction due to production from the formation. The change in the pore pressure serves to promote change in the total and effective stresses [13]. As more fluids leave the pore space, the reservoir pressure will reduce. This allows the effective stress to increase and the rock shrinks, leading to compaction. This stress change is usually dependent on the *in situ* stresses, rock geometry, and mechanical properties. The stress changes are defined in terms of stress path coefficients, which are easily obtained for an isotropic change. Under a triaxial stress system, a change in pore pressure promotes a change in the effective stress and total stress as follows, [13]:

$$\Delta\sigma_v' = \Delta\sigma_v - \alpha\Delta p \tag{1}$$

$$\Delta\sigma'_h = \Delta\sigma_h - \alpha\Delta p \tag{2}$$

Where $\Delta\sigma'_v$ = change in effective vertical stress, $\Delta\sigma_v$ = change in total vertical stress, Δp = change in pore pressure, α = Biot`s coefficient, $\Delta\sigma'_h$ = change in effective horizontal stress, and $\Delta\sigma_h$ = change in horizontal stress.

The three stress path parameters, for triaxial stresses, introduced to define the stress changes are the following expressions [5]:

$$\gamma_v = \frac{\Delta\sigma_v}{\Delta p} \tag{3}$$

$$\gamma_h = \frac{\Delta\sigma_h}{\Delta p} \tag{4}$$

$$k = \frac{\Delta\sigma'_h}{\Delta\sigma'_v} \tag{5}$$

Where γ_v = vertical stress path parameter, called the stress arching, γ_h = horizontal stress path parameter, k = deviator parameter.

In eq. (3) to eq. (5), the intermediate stress does not play any part, as the horizontal stresses are equal. This is not always the case for a 3D formation, where the horizontal stresses are unequal. Thus, it is important to introduce the intermediate stress path parameter to account for polyaxial compaction in a formation. During loading, part of the overburden stress transmits to the sides of the formation, a phenomenon that is known as stress arching ([14], [15]). Depleted reservoirs are good candidates for wellbore stability analysis and can serve as sites for CO_2 sequestration and infill drilling [5]. The reduction in pore pressure leads to a reduction in horizontal stresses, which implies a reduction in the fracture gradient. Wellbore collapse and/or wellbore fracture ensue in such a well. From stress evolution studies, pore-collapse prediction, reactivation of faults and bedding parallel slip prediction are possible, [16].

The aim of this study is to develop a model for reservoir compaction from the theory of polyaxial stress state, useable in geomechanical studies. The objectives of the study are to devise a scheme for obtaining the intermediate stress path parameter, then to estimate the vertical compaction of reservoir rocks in terms of pore pressure depletion and to consider the variance between uniaxial and polyaxial compactions. In addition, the authors strive to produce a monograph for quick read-up of vertical compaction in a depleted reservoir.

II. LITERATURE

Rock compaction can be plastic or elastic Rock compaction can be plastic or elastic, ([2], [3]), the former entails the squeezing of minerals such as shale and clays into pore spaces as reservoir pressure increases and pore fluids flow out [1]. When rocks compact this way, they do not return to their initial volume upon removal of the load. For elastic compaction, the rock can return to almost its initial volume upon removal of the load. This depends on hysteresis. Reservoir compaction can be modeled using 3D or 1D analytical solution, depending on the complexity of the reservoir [17]. From the 1D analysis, critical parameters are understood and the importance of 3D modeling becomes obvious. More importantly, poor estimation of rock compaction can lead to the wrong estimation of reserves [18]. The method used in obtaining reservoir compaction is to determine earth deformations from the constitutive strain-stress equations of the poroelastic material. Then, the uniaxial compaction is obtained from the vertical strain. The pre-requisite for the estimation is the knowledge of the stress evolution in the formation ([5]; [19]; [13]).

Fjær *et al* [5] developed a model for uniaxial compaction using Hooke`s law. They gave the model in terms of depletion in reservoir pressure. Linear poroelastic theory in a homogeneous reservoir formed the basis of the study. The rock properties used for the study were isotropic, but most sedimentary rocks have large-scale anisotropy. The elastic modulus of anisotropic rocks varies from one direction to the other. This intrinsic or induced anisotropy, when not included in the analysis, can yield errors. The mathematical expressions for the changes in effective stress obtained are the following:

$$E\varepsilon_h = \Delta\sigma_h - \nu\left(\Delta\sigma_H + \Delta\sigma_v\right) \tag{6}$$

$$E\varepsilon_H = \Delta\sigma_H - \nu\left(\Delta\sigma_h + \Delta\sigma_v\right) \tag{7}$$

$$E\varepsilon_v = \Delta\sigma_v - \nu\left(\Delta\sigma_H + \Delta\sigma_h\right) \tag{8}$$

Where E = average elastic modulus, ε_h = strain in the minimum stress direction, ε_H = strain in the intermediate stress direction, ε_v = strain in the maximum stress direction, $\Delta\sigma_h$ = stress change in the minimum effective stress direction, $\Delta\sigma_H$ = stress change in the intermediate effective stress direction, $\Delta\sigma_v$ = stress change in the maximum effective stress direction, and ν = Poisson`s ratio.

From eq. (6), eq. (7) and eq. (8), rocks with anisotropic elastic constants may not be solvable. It is important to develop models that are robust enough to incorporate anisotropy in elastic moduli. The result for the vertical compaction is the following model for strain [5], obtainable from eq. (8):

$$\varepsilon_v = -\frac{\Delta h}{h} \tag{9}$$

Where h = reservoir thickness and Δh = vertical compaction of the rock.
Upon the assumption of no lateral compactions, [5] gave an expression for reservoir compaction as the following:

$$\frac{\Delta h}{h} = \left(\frac{1-\nu-2\nu^2}{1-\nu}\right)\frac{\alpha \Delta P_p}{E} \tag{10}$$

Where ΔP_p = pore pressure depletion and α = Biot`s coefficient, taken as unity in this study. The limitation of using uniaxial compaction in geomechanics is that when the theory deviates from reservoir condition, the results are not representative of *in situ* mechanical behavior. Teufel *et al.* [19] analyzed compaction and subsidence in the Ekofisk reservoir and showed the importance of stress-path analysis. Their study showed that for measurements during pore pressure depletion, the increase in effective horizontal stress was lower than that obtained from the laboratory. Hettema *et al.* [20] did an extensive study on the stress path coefficient for stress changes during pore pressure depletion. Rotational symmetry in the horizontal plane is the assumption used in obtaining the parameters for analyzing uniaxial compaction [5]. This will not yield a good result when we analyze polyaxial stresses, with different horizontal stresses. In an experiment designed to deform samples of rocks, constrained by uniaxial stresses up to 30kN in magnitude, [21] observed widespread small-scale fractures in the more porous rocks. These fractures are indicative of the movement of *in situ* stresses in three dimensions and not just in one direction. The presence of faults and fractures, at large scale, result from stress differentials among the *in-situ* stresses. It is, therefore, better to consider compactions in 3D. Rock compaction is stress-path dependent, ([22], [5], [13]), thus we may expect variations in results when *in situ* stresses are polyaxial. Moreover, we can use these stress-path parameters to obtain vertical compaction from the polyaxial stress system.

Expressions for the stress path parameters can be obtained using the [23] model, which relates the aspect ratio (ratio of thickness to length of the reservoir) with the coefficients. However, a more simplified set of expressions is the [24] model for flat reservoirs, which are given as follows:

$$\gamma_v = \frac{(1-2\mu)\alpha}{(1-\mu)}\frac{\pi}{2}e \tag{11}$$

$$\gamma_h = \frac{(1-2\mu)\alpha}{(1-\mu)}\left(1-\frac{\pi}{4}e\right) \tag{12}$$

Where e = aspect ratio, α = Biot`s coefficient, $\mu$ = Poisson`s ratio. With eq. (11) and eq. (12), the stress path parameters are now with respect to the geometry of the reservoir, thus variations in reservoir dimensions can be observed. These stress paths are for total stresses in the formation. More useful to the current study is the effective stress path parameters, which can be written as follows [5]:

$$\gamma' = \gamma - \alpha \tag{13}$$

Where γ' = the effective stress path parameter in the direction considered, γ = total stress path parameter in the direction considered, and α = Biot`s coefficient. With eq. (13), the expressions for the effective stress paths in the orthogonal directions can be presented, but the stress path parameter in the intermediate direction is a requirement. An important technique of obtaining intermediate property of a system is by the use of averaging/interpolation technique. The Lagrange averaging [25] of the stress path coefficients in the maximum and minimum stress directions can yield a result for that in the intermediate stress direction. We can do this since both the *in situ* stresses and their changes are orthogonal. Stress-path coefficients should be orthogonal, except where there are, for example, equal lateral stresses.

Recently, [26] used geomechanical simulation to study the subsidence and compaction behavior of the Fahlian reservoir of Iran. The available data fed into the simulator included geophysical, geological, reservoir engineering and geomechanical data. They used these data to calculate the magnitude and orientation of the *in situ* stresses, with about a 90% correlation between model and real data. The results showed that reservoir compaction and subsidence were insignificant in the field, at about 29 mm, mainly because of the gas injection scheme used in the formation. Large-scale injection into a formation can reduce the compaction and subsidence significantly because it serves to support the rock strength. Their study showed the importance of accurately developing 3D geomechanical models. The basis for the 3D geomechanical model generated was the building of a 1D model for wells in the field.

III. METHODOLOGY

From Hooke`s law of elasticity, we obtained the various strains in the minimum, intermediate and maximum stress directions using a computer application. The stress evolutions in the formation were obtained in terms of the effective stress path parameters in the three orthogonal directions such that 3D responses were obtained. In order to obtain the effective stress-path parameter in the intermediate principal stress direction, we used the Lagrange averaging of results between those of the vertical and minimum horizontal stresses. We computed the vertical compaction from eq. (4), and showed the variation between the polyaxial compaction and a uniaxial one as obtained by [5].

Fig. 1 shows the physical model for the study, which is a rectangular geometry that comprises vertical and lateral stresses. There was no assumption of zero lateral strains in this study, which is the convention used in the 1D analysis. This is a true representative of polyaxial stress systems.

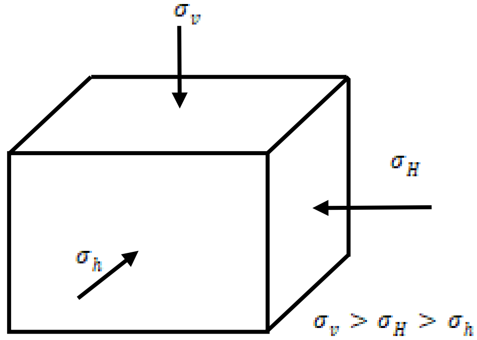

Fig. 1- physical model of stresses on the rock

In order to incorporate the possibility of modeling the effect of anisotropy, a new set of equations for the Hooke`s law are posed as follows:

$$E_h \varepsilon_h = \Delta\sigma_h - \nu(\Delta\sigma_H + \Delta\sigma_v) \tag{14}$$

$$E_H \varepsilon_H = \Delta\sigma_H - \nu(\Delta\sigma_h + \Delta\sigma_v) \tag{15}$$

$$E_v \varepsilon_v = \Delta\sigma_v - \nu(\Delta\sigma_H + \Delta\sigma_h) \tag{16}$$

Where E_h = elastic modulus in the minimum horizontal stress direction, E_H = elastic modulus in the maximum horizontal stress direction, E_v = elastic modulus in the vertical stress direction, ε_h = strain in the minimum stress direction, ε_H = strain in the intermediate stress direction, ε_v = strain in the maximum stress direction, $\Delta\sigma_h$ = stress change in the minimum effective stress direction, $\Delta\sigma_H$ = stress change in the intermediate effective stress direction, $\Delta\sigma_v$ = stress change in the maximum effective stress direction, and ν = Poisson`s ratio.

From eq. (13), the following expressions for the effective stress path parameters are posed:

$$\gamma'_v = \gamma_v - \alpha \tag{17}$$

$$\gamma'_h = \gamma_h - \alpha \tag{18}$$

$$\gamma'_H = \gamma_H - \alpha \tag{19}$$

Where the superscript are as defined in eq. (13) and the subscripts v, h, and H represent the vertical, minimum horizontal and maximum horizontal directions respectively. From eq. (3) and eq. (4), the values of the stress path parameter in the vertical stress direction and in the minimum horizontal stress direction relates to the *in situ* stresses linearly. Then, the application of the Lagrange averaging techniques [25], on the *in situ* stresses yields the following expression for the stress path parameter in the maximum horizontal stress direction:

$$\gamma_H = \gamma_h - (\gamma_h - \gamma_v)\left(\frac{\sigma_h - \sigma_H}{\sigma_h - \sigma_v}\right) \tag{20}$$

Where γ_h = stress path coefficients in the minimum horizontal stress direction, γ_H = stress path coefficient in the maximum horizontal stress direction, γ_v = stress path coefficient in the vertical stress direction, σ_h = minimum horizontal stress, σ_H = maximum horizontal stress and σ_v = vertical stress.

From eq. (14), eq. (15) and eq. (16), we have the matrix arrangement for the effective compactions in the rock as follows:

$$\begin{pmatrix} \varepsilon_h \\ \varepsilon_H \\ \varepsilon_v \end{pmatrix} = \begin{pmatrix} 1 & -\mu & -\mu \\ -\mu & 1 & -\mu \\ -\mu & -\mu & 1 \end{pmatrix} \begin{pmatrix} \gamma'_h \dfrac{\alpha \Delta p}{E_h} \\ \gamma'_H \dfrac{\alpha \Delta p}{E_H} \\ \gamma'_v \dfrac{\alpha \Delta p}{E_v} \end{pmatrix} \tag{21}$$

We can, therefore, extract expression for the vertical compaction, as follows:

$$\Delta h_v = \left(\frac{\gamma'_v}{E_v} - \mu \frac{\gamma'_h}{E_h} - \mu \frac{\gamma'_H}{E_H} \right) \alpha \Delta P_p h \tag{22}$$

Eq. (22) can model compaction for rocks with contrasting elastic moduli, but obtaining this information is very difficult in reservoir studies. In order to simplify the analysis, the elastic constant can be taken as uniform, except where such data are measurable.

In order to develop a workflow for obtaining polyaxial compaction in this study, MS excel computer capability was employed. This workflow requires reservoir input data, which are geomechanical and has an allowance for elastic constant anisotropy. Equation (11), (12), and (17)-(20) were combined to obtain the effective stress path parameters, while eq. (21) yielded the result for the vertical strain, from where the compaction was obtained. We also randomly generated a thousand data points in the interval $0.5-1$ to satisfy the condition that $\gamma_h < \gamma_H < 1$. In addition, the results of the prediction from the Lagrange interpolation were in agreement with those from randomly generated stress path parameters, hence the results, in **Fig. 5** can serve as a quick read-up chart.

IV. RESULTS AND DISCUSSION

From eq. (22), we observe a smaller compaction in the reservoir than in a uniaxial model, eq. (10), which is obtainable assuming the stress path parameters are equal in the horizontal directions. With this development, reservoir subsidence for uniaxial compaction would probably yield poor results if polyaxial stress state were present. Reservoir compaction depends on the stress regime in a formation. Under a normal stress regime, the results of polyaxial compaction are significantly different from those of uniaxial compaction. The reason is that the stress-path coefficients change as the stress regimes change. The difference may be larger in a strike-slip regime or reverse stress regime. Using the data in **Table 1,** we obtained a compaction of 0.503 ft by applying the uniaxial model, [5], while the current model yielded a compaction of 0.4656 ft, which is about 7.9% smaller in value. In practical design, this can be economically catastrophic as poor reservoir management ensues.

Table 1: Properties for a disk-shaped reservoir compaction

	Parameter	Symbol	Value	Unit
1	Overburden stress gradient	σ_o	0.953	[Psi/ft]
2	Pore pressure gradient	P_p	0.45	[Psi/ft]
3	Maximum horizontal stress, gradient	σ_H	0.8	[Psi/ft]
4	Minimum horizontal stress, gradient	σ_h	0.7	[Psi/ft]
5	Reservoir depth,	Z	6560	[ft]
6	Reservoir thickness,	h	328	[ft]
7	Poisson`s ratio,	ν	0.25	[-]
8	Shear modulus,	G	2	[GPa]
9	Depletion,	ΔP	10	[MPa]
10	Reservoir Diameter	D	6560	[ft]

Compaction is linear with pressure depletion but inversely proportional to rock stiffness. Thus, soft reservoirs will show more compaction than corresponding stiff ones [5]. The thickness of the rock plays a similar effect on polyaxial compaction as in the uniaxial case. A rock with smaller thickness will compact less than one with larger thickness depending on the stiffness and compression of the sediments. Any reservoir system that tends to improve pore pressure will reduce compaction. For example, an energy supplement from an external aquifer or the introduction of injection wells.

The variance between the values of polyaxial and uniaxial compactions can affect the modeling of surface subsidence. This may also affect the integrity of the wellbore casings. Polyaxial compaction decrease with increasing Poisson`s ratio, muck like uniaxial compaction. Both types of compactions tend to approach zero as Poisson`s ratio approaches 0.5, at which point the rock behaves as a plastic and there exists little or no difference between them. **Fig. 2** shows the variation of both polyaxial and uniaxial compactions with Poisson`s ratio, while **Fig. 3** shows the variation of absolute difference in compactions with Poisson`s ratio.

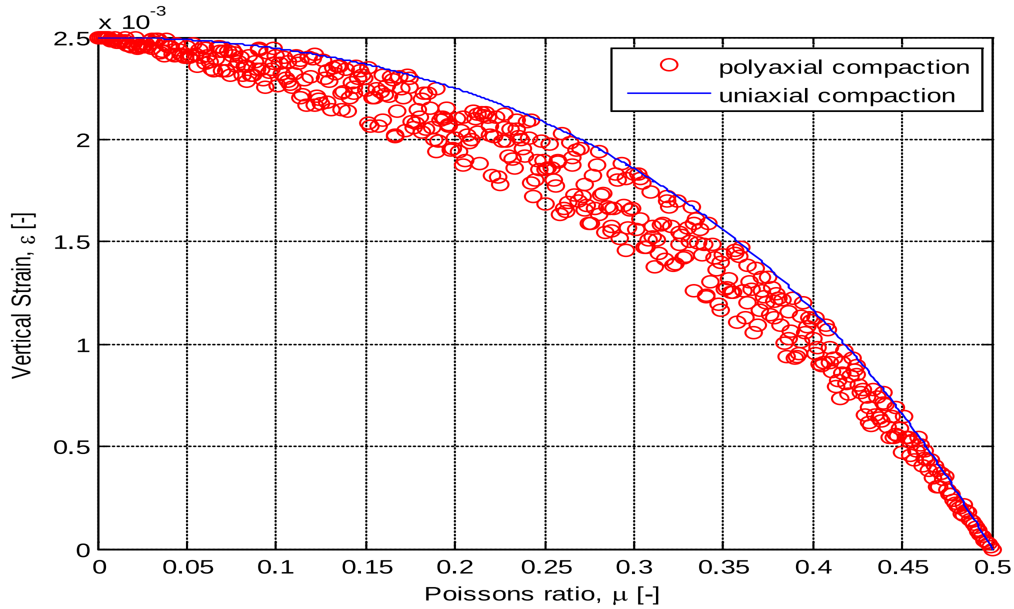

Fig.2- Variation of polyaxial and uniaxial compactions with Poisson`s ratio.

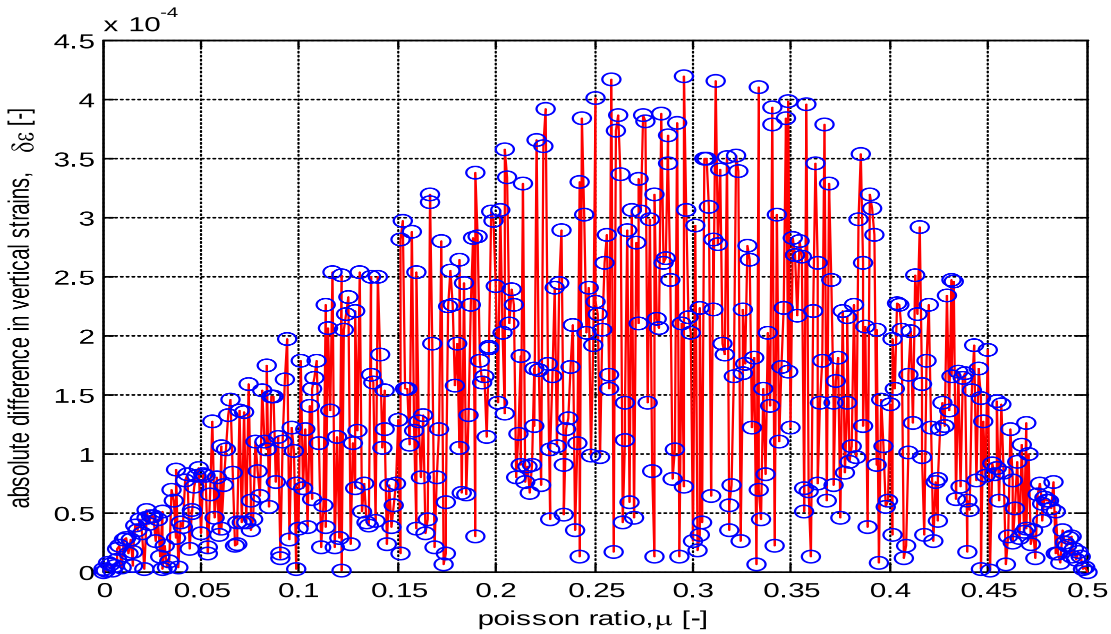

Fig.3- Variation of difference in compactions with Poisson`s ratio.

The simulation was repeated several times and the maximum difference observed between the compactions occurs at Poisson`s ratio equal to or greater than 0.25 in all cases, as the distribution was observed to be slightly non-symmetrical. This is within significant depth in the formation.

The reservoir thickness affects the results of rock compaction. Varying the thickness from 0-200m, the magnitude of the compactions changes significantly. As the aspect ratio of the rock increases, due to increasing reservoir thickness against reservoir length, both the uniaxial and polyaxial compactions increase up to a point and then starts to reduce in value with a trend reversal. During the trend reversal, the value of the polyaxial compaction becomes larger than that of the uniaxial compaction as shown in **fig. 4.** The compaction of the reservoir is transferred easier in the direction of the lower length scale. As the reservoir thickness gets larger with respect to the lateral scale, the compaction increases in that direction.

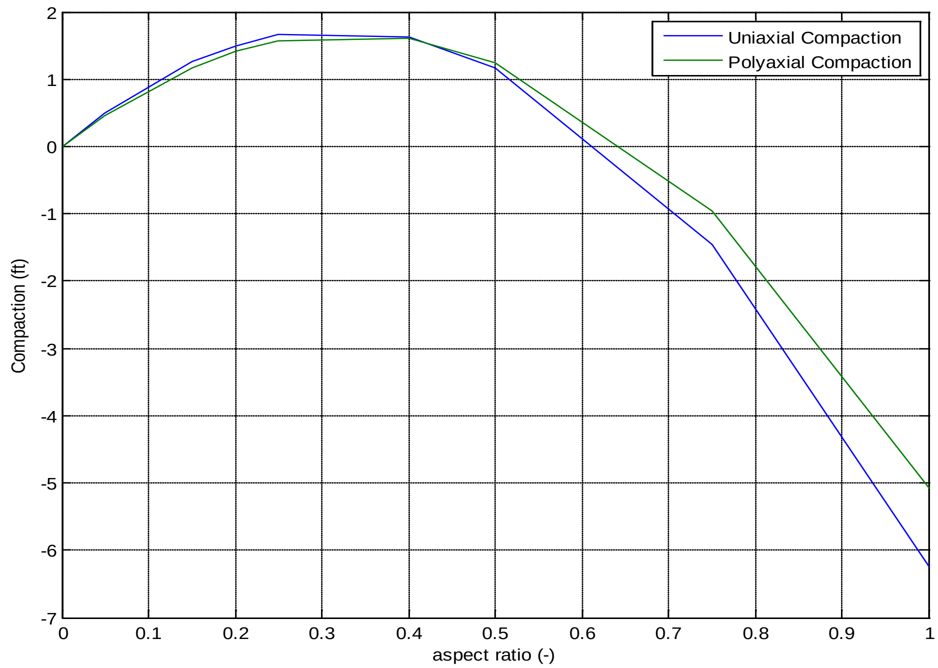

Fig.4- Plot of aspect ratio against compaction

Variation of compaction with elastic moduli contrast

Up till this point, the compactions has been with respect to an isotropic rock, with uniform elastic constant. Incorporating the effect of the elastic contrast with allowance for maximum, intermediate and minimum elastic constant, various results are obtained. When applied to the elastic contrast with the condition such that $6Gpa > 5Gpa > 4Gpa$, the following are obtained when the various constants are maximum, intermediate and minimum elastic constants. The uniaxial compaction has higher values than the polyaxial compaction when the elastic constant in the vertical direction is higher than that in the least horizontal stress direction, $E_v > E_h$, while the polyaxial compaction yields higher values when the elastic constants in the horizontal stress directions are higher than that in the vertical stress direction. When the elastic constant in the vertical direction is intermediate between those of the horizontal directions, the uniaxial computation result is higher than the polyaxial value. The various results are displayed in **table 2.**

Table 2: Effect of elastic constant anisotropy on compactions.

Condition	Uniaxial Compaction, ft	Polyaxial Compaction, ft
$E_v > E_h > E_H$	**0.4198**	**0.3377**
$E_v > E_H > E_h$	**0.4198**	**0.3473**
$E_H > E_v > E_h$	**0.5037**	**0.4670**
$E_H > E_h > E_v$	**0.6297**	**0.6372**
$E_h > E_H > E_v$	**0.6297**	**0.6308**
$E_h > E_v > E_H$	**0.5037**	**0.4512**

The elastic constant is proportional to the stress, which has been related to the pressure depletion. The lower the elastic constant in a particular direction, the higher the strain in that direction, which corresponds to higher compaction. This reflects the results obtained in **table 2** for higher values of polyaxial compaction compared to uniaxial compaction when the vertical elastic constant is lower than the lateral one. The deposition of different layers of sediments can result in different elastic constants obtained in a formation, [5]. Thus, it is very important to determine whether elastic constants vary in a formation or not before computation of compactions. This can significantly affect subsidence in a locality. From table 1, the largest difference between polyaxial compaction and uniaxial compaction occurs when the vertical elastic constant is greater than the horizontal components.

A-50,000-Simulation run for rock compactions was obtained using 50,000 trials in the Optquest application. **Fig 5** shows the sensitivity chart for the polyaxial compaction. In order to facilitate the simulation run, twelve (12) assumptions of the reservoir geomechanical properties and a decision variable as Biot`s constant were used to forecast six (6) parameters including uniaxial and polyaxial compactions, aspect ratio, and the three (3) effective stress path parameters. The results show that the pore pressure depletion (30.7%), reservoir thickness (25.7%), and the intermediate *in-situ* stress (18%) significantly influence the result of the polyaxial compaction. The Poisson`s ratio (16.1%) also greatly influences the results of the compaction. Thus, if the maximum horizontal stress significantly differs from the minimum horizontal stress in the formation, the compaction can exceed uniaxial compaction. The most influential parameter of the compaction is the depletion of pore pressure, without which there can be no void in the rock to cause settlement. This result is consistent with the previous study by [5], which implies that pore pressure depletion controls compaction, subsidence, and fluid flow performance in a reservoir.

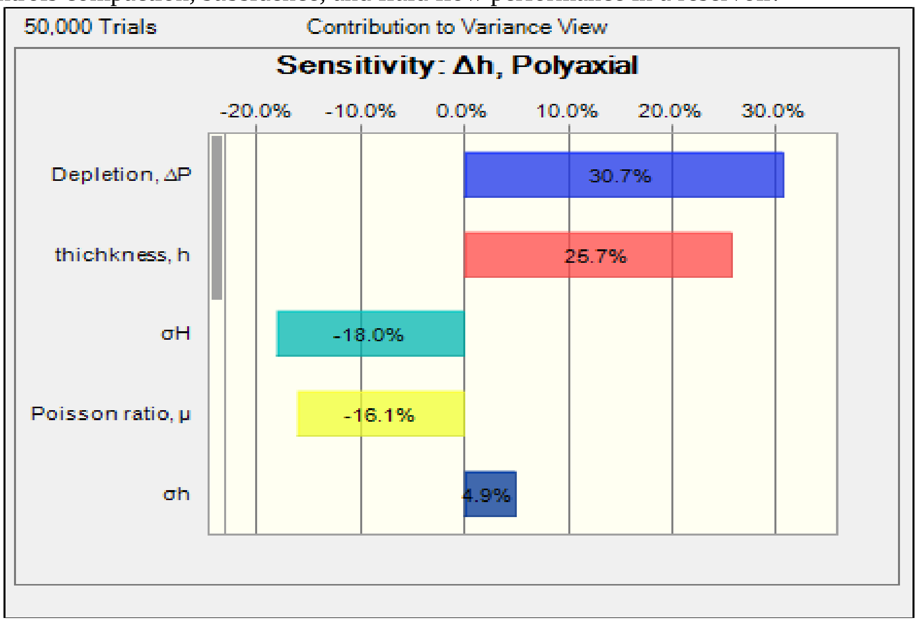

Fig 5: Sensitivity of polyaxial compaction to geomechanical properties for 50000 simulations

For the sensitivity chart of parameters affecting uniaxial compaction, **fig. 6** shows the result. The chart shows that, in order of decreasing magnitude, the pore pressure depletion (43.7%) is still the most significant parameter affecting compaction, followed by the reservoir thickness (36.6%) and Poisson`s ratio (19.3%). From the results of **fig. 5** and **fig. 6,** pore pressure depletion and a considerable thickness must be present for compaction to occur.

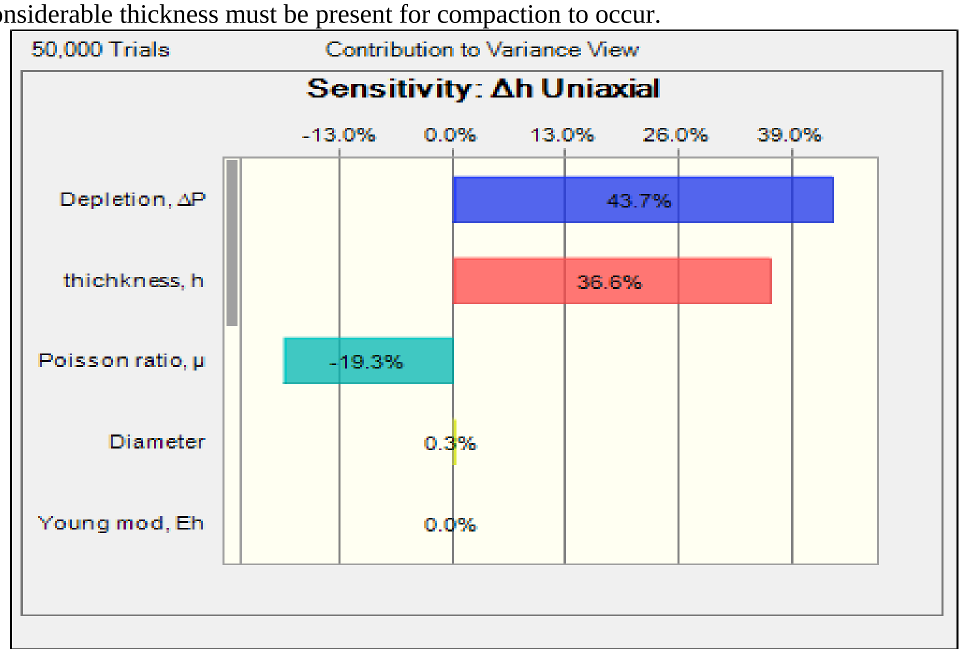

Fig 6: Sensitivity of uniaxial compaction to geomechanical properties under 50000 simulations

The effective stress path parameter in the vertical direction is highly sensitive to the reservoir thickness, depth and Poisson`s ratio; while in the minimum horizontal stress direction, the stress path parameter is highly dependent on the Poisson`s ratio as shown in the appendix (**fig. A).** The effective stress path parameter in the maximum horizontal stress direction is highly sensitive to the *in situ* stress fields and Poisson`s ratio. The magnitude of the intermediate stress is the major contributor. Previous studies ([5], [13]) show that the vertical and horizontal stress path coefficients depend on the geometry of depleting formation and on the elastic contrast between the rock and its surrounding.

We provide a monograph, **Fig.7**, serving as a chart for quick read-up of vertical compaction in the depleted reservoir considered at various values of the Poisson's ratio. The requirements for using the chart are the intermediate stress-path parameter and the Poisson`s ratio.

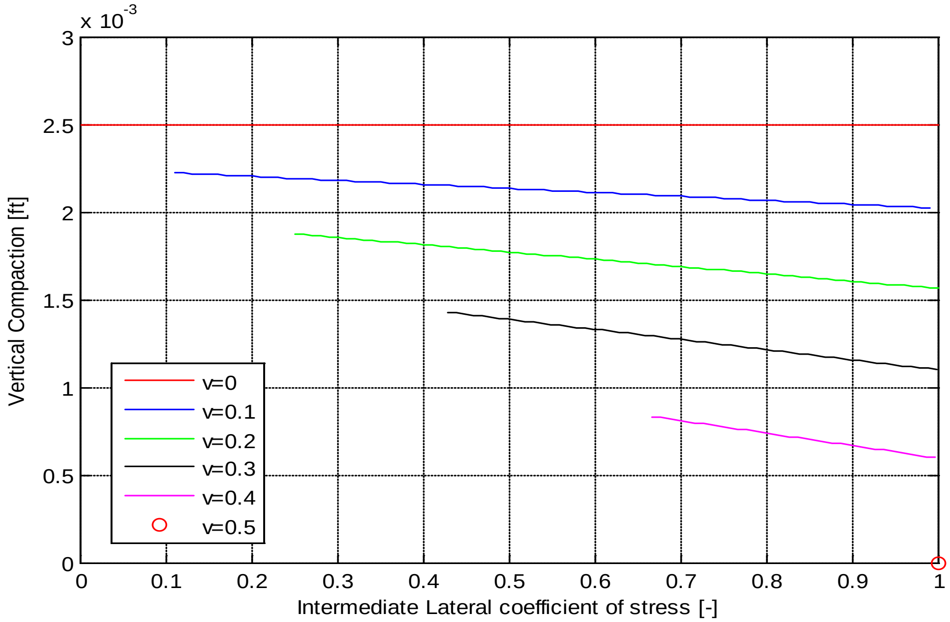

Fig.7- Monograph containing vertical strain, Poisson`s ratio, and intermediate stress coefficient

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V. CONCLUSION

In this study, we have examined reservoir compaction in terms of effective stress path parameters, and changes in polyaxial stresses, pore pressure depletion, and varying elastic moduli, which helps to incorporate the effect of anisotropy. From the results, we have the following points:

- In the vertical direction, polyaxial Compaction mainly yields lower values than in a corresponding uniaxial compaction, with the uniaxial compaction defining the envelope or upper bound of possible compactions.
- The difference between polyaxial and uniaxial compactions diminishes in the region of plastic behavior.
- The distribution of the Difference in polyaxial and uniaxial compactions with Poisson`s ratio follows a near parabolic trend or a bell-shaped distribution.
- Polyaxial compaction has a magnifying effect in a formation when the elastic constant in the least horizontal stress direction is larger than in the vertical one.
- The largest variation between uniaxial compaction and polyaxial compaction occurs when the vertical elastic constant is the largest in the formation.
- The maximum horizontal principal stress plays a significant role in the development of polyaxial compaction in a reservoir.

We, therefore, recommend further studies in this area of geomechanics, especially using different stress regimes.

APPENDIX

SENSITIVITY CHART FOR ASPECT RATIO AND EFFECTIVE STRESS PATH PARAMETERS

Fig AA: Sensitivity of aspect ratio (e), vertical stress path parameter (γ_v), and horizontal stress path parameters (γ_h and γ_H).

REFERENCES

[1] A.I. Levorsen, "Geology of petroleum", 2nd edition, CBS Publishers, New Delhi, ISBN: 81-239-0931-4, 1966, pp 401-402.

[2] A. C. Fowler, X. Yang, Pressure solution and viscous compaction in sedimentary basins, Journal of Geophysical Research, Vol. 104, B6, 1999, pp. 12987-12997.

[3] X.S. Yang, Pressure Solution in Sedimentary Basins: effect of Temperature Gradient, Earth and Planetary Science Letter, 176, 2000, pp. 233-243.

[4] R.F. Mitchell, S.Z. Miska, "FUNDAMENTALS OF DRILLING ENGINEERING", SPE TEXTBOOK SERIES, Vol. 12, 2011, pp. 76.

[5] E. Fjær, R. Holt, P. Horsrud, A.M. Raaen, and R. Risnes, "*Petroleum Related Rock Mechanics*", 2nd Edition, Elsevier, Amsterdam, 2008, p.338.

[6] R. Sulak, "Ekofisk field: the first 20 years", J Pet Technol 43(10):1,1991, 265–261,271

[7] Al-Ajmi, A.M. Wellbore stability analysis based on a new true-triaxial failure criterion, TRITA-LWR, Ph.D. Thesis, 2006, 1026.

[8] E. M. Anderson, "*The Dynamics of Faulting and Dyke Formation With Applications to Britain*", Edinburgh, UK: Oliver and Boyd, 1951.

[9] D. A. Castillo, M. D. Zoback, "Systematic stress variations in the southern San Joaquin Valley and along the White Wolf fault: Implications for the rupture mechanics of the Ms 7.8 Kern County earthquake and contemporary seismicity", *J. Geophys. Res.* **100** (B4): 1952, 6249-6264. http://dx.doi.org/10.1029/94jb02476.

[10] A. Zang, O. Stephansson, Stress field of the earth crust, Springer Science, 2010, pp 11-32. ISBN: 978-1-4020-8443-0.

[11] I. Song, B. C. Haimson, Polyaxial strength criteria and their use in estimating *in-situ* stress magnitudes from borehole breakout dimensions. *Int J Rock Mech Min Sci*, 1997, 34 [3-4].

[12] L. Vernik, M. D. Zoback, "Estimation of maximum horizontal principal stress magnitude from the stress-induced wellbore breakouts in the Cajon Pass scientific research borehole". *J Geophys Res*, 97 [B4], 1992, 5109-5119.

[13] J.M. Segura, Q.J. Fisher, A.J.L. Crook, M. Dutko, J. Yu, S Skachkov, D.A. Angus1, J. Verdon, M. Kendall. Reservoir Stress Path Characterization and its Implications for Fluid- Flow Production Simulations, Petroleum Geoscience, 2017, pp 1-16.

[14] M. Khan, Teufel LW, Zheng Z. Determining the effect of geological and geomechanical parameters on reservoir stress path through numerical simulation, *Society of Petroleum Engineers* paper 63261, presented at the 2000 SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA: 2000.

[15] C.M. Sayers, MTM Schutjens. An introduction to reservoir geomechanics, *The Leading Edge*, May 2007: 597-601.

[16] Verdon, JP, Kendall, JM, White, DJ, Angus, DA, Fisher, QJ, Urbancic, T. Passive seismic monitoring of carbon dioxide storage at Weyburn, The Leading Edge, 29(2), 2010, 200-206.

[17] www.ikonscience.com/solutions, "Reservoir compaction and subsidence", 2017.

[18] A Settari, "Reservoir compaction", J Pet Technol 54(08), 2002, 62–69

[19] L. W. Teufel, D. W. Rhett, H. E. Farrell, "Effect of reservoir depletion and pore pressure drawdown on *in-situ* stress and deformation in the Ekofisk field, North Sea". In: Proc. 32nd U.S. Symp. on Rock Mechanics, Norman, OK, USA, 1991, pp. 62–73.

[20] M. H. H., Hettema, P. M. T. M. Schutjens, B. J. M. Verboom, H. J. Gussinklo, "Production-induced compaction of a sandstone reservoir: The strong influence of stress path". SPE Reservoir Evaluation Eng. 3, 2000, 342–347.

[21] W. F. Brace, D. K. Riley, "Static uniaxial deformation of 15 rocks to 30kb, International Journal of Rock mechanics & mining Science & Geomechanics Abstract, 9 (2), 1972, 271-288.

[22] B. R. Crawford, P. F. Sanz, B. Alramahi, N. L. DeDontney, "Modelling and predicting of formation compressibility and compactive pore collapse in siliciclastic reservoir rocks", Presented at the 45th US Rock Mechanics Symposium, San Francisco, CA, USA, 26-29 June 2011.

[23] J. Rudnicki. "Alteration of regional stress by reservoirs and other inhomogeneities: stabilizing or destabilizing?" In: Proceedings of the 9th International Congress on Rock Mechanics 3, 1999, pp. 1629–1637.

[24] Segall, P., Fitzgerald, S.D. "A note on induced stress changes in hydrocarbon and geothermal reservoirs". Tectonophysics 289, 1998, 117–128.

[25] P. Phillip, Numerical analysis 1, LMU, Munich, 2013, Pp. 40.

[26] Ranjbar, A., Hassani, H. & Shahriar, K. Arab, "3D geomechanical modeling and estimating the compaction and subsidence of Fahlian reservoir formation (X-field in SW of Iran)", J Geosci, 2017, 10: 116. https://doi.org/10.1007/s12517-017-2906-3.

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