Optimal Vertical Placement of Well pairs in SAGD

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Spatial location of well pairs plays an important role in the production of bitumen from steam assisted gravity drainage (SAGD) processes. Horizontal well pairs are drilled in areas of high reservoir quality, the drilling depth should be selected in such a way that the production of bitumen is maximised. This paper discusses a methodology to explore the two main aspects of vertical positioning of a well pair (1) elevation for maximum bitumen recovery, and (2) quantify and address the uncertainty/risk associated with well elevation. Placing a well pair deeper into a bitumen deposit can give access to more bitumen volume, but at the same time uncertainty in the base of bitumen must be considered to minimize the loss of steam in unproductive regions. A methodology is presented to determine the optimal vertical placement of a well and address the corresponding uncertainty associated with different vertical elevations of a well pair. `WellVertPos` *is developed for this purpose and results have been presented based on hypothetical examples. These examples have been generated in order to explain the effect of the shape of the base continuous bitumen (BCB) surface on optimal well elevation.*

1. Introduction

SAGD is an enhanced oil extraction process from thick bitumen deposits that are too deep to economically mine. It is a two step process: first bitumen is heated by superheated steam to decrease the viscosity of thick bitumen, then melted bitumen is transported up to the surface by means of a production well. The methodology is shown in Figure 1, two horizontal wells are drilled in the deposit, one well is used to inject heated stem into the deposit (red), and the other well collects the melted bitumen and transports it to the surface (green). For a detailed description of SAGD see the CCG guide book on SAGD (Deutsch and McLennan , 2005)

Two wells of a single SAGD well pairs are located at same areal location .i.e. the x, y coordinates are identical for both horizontal wells. The vertical differences between horizontal well pairs are generally fixed (~ 5m). The length of well pairs may vary (800 – 1200 m). In practice many well pairs are drilled in a group to cover a good reservoir area, such clusters of well pairs are termed a Drainage Area (DA). Even after selecting a good areal location of well pairs it is very important to drill a well pair at a vertical depth which maximises the recovery and/or profit and at the same time minimizes the risk of passing wells through impermeable rock types.

2. Vertical location

SAGD extraction of bitumen is dependent on gravity; therefore, anything below the producer well can't be accessed, placing producer well at higher elevations may reduce recovery. Conversely, placement of wells at a greater depth may cause parts of a well to pass through a non-porous medium such as shell types of rock deposits and reduces recovery as this well section is not being used to collect melted bitumen. Another negative effect of having a portion of the producer well in a non-porous medium is that the absence of nearby steam chambers. In the beginning of the SAGD process both horizontal wells are used to inject steam into the reservoir to make a steam chamber [1]. If some well lengths of producer wells are lost into a non porous deposit, then no steam chamber is formed and no production of bitumen may occur in that part of the well. Figure 1 explains the problem of well pairs that are drilled too high. The lost of resource in the case of low elevation of producer is explained in Figure 2.

Bitumen deposits are generally entrapped in a porous medium such as sandstone. At the bottom and top boundary of the deposit, non-porous rock such as shell is present which define the limits of the deposit; the top of the deposit is the top continuous bitumen (**TCB**), with the bottom continuous bitumen (**BCB**) defining the deposit extents. Any part of the production well below the BCB surface is non-productive and is lost well length. Figure

2(a) shows the schematic representation of the lost well length. The gray color surface represents the BCB surface and the production well is shown in green. AA' highlights a lost well length.

The recoverable part of a bitumen deposit in the vicinity of a lost well length can be represented as in Figure 2(b). The simplest assumption about the volume of the unrecoverable resource due to lost well length is the cuboid; however, this type of assumption is unrealistic as steam from other well sections melts a portion of the volume of bitumen inside the cuboid. A more realistic assumption is that a cone surface defines the steam chamber at the beginning and the end points of the lost well length (points A and A').

Trying to minimize the amount of lost resource by increasing the depth of a well may result in an increase in the amount of unrecoverable resource. An optimum balance in both types of losses maximizes the overall recovery of bitumen from a given well pair. Other important factors relating to unrecoverable bitumen volume are:

- Amount of unrecoverable and lost bitumen is not the direct function of volume but depends on the quality of reservoir inside the volume (facies type, porosity, permeability etc.).
- Volume of unrecoverable resource is not a linear function of the length of lost well length. A larger length will have more volume of unrecoverable resource than smaller length of lost well length. For example a total of 100 m of lost well at 10 different locations is better than a single segment of lost well with length of 100m.

3. Methodology:

It is the elevation of producer well which is considered for the optimization. Because the initial steam chamber growth is related with producer well, if any part of well is lost then there will be no steam chamber at that section (Deutsch and McLennan, 2005). Optimum well elevations are determined based on 3D geological realization of the deposit. Many realizations of different reservoir variables such as: (1) facies type (sandstone, mudstone, shell etc), (2) Porosity, (3) water saturation, and (4) vertical permeability should be considered in the modelling process. Another variable important to well elevation optimization is the BCB. Material below the BCB surface is considered inaccessible for any elevation of a well pair. Since BCB is the elevation of the bottom surface, only 2D modelling is required. In the presented methodology the number of realizations of BCB considered is the same as the number of realizations of reservoir variables. Locating the optimum well depth and addressing the uncertainty in recoverable reserves is a 2 step process:

1. For each 3D geological realization of reservoir variables:
    a. Change the elevation of well inside the limits of TCB and BCB and calculate the overall recovery or each such well elevation.
    b. Select the elevation with maximum objective value.
2. Calculate the mean profile of dept vs. recoverable reserves and depth vs. uncertainty in recoverable reserves.

To determine the optimal vertical well elevation and associated uncertainty the following steps are required:

4. *Re-girding the realizations in the cuboid inclosing well pair-* Based on the location of the producer well, the realization data is regridded to align with the direction of the well pair (Figure 3). The resolution of the grid can be increased for more precise calculations. The x-direction of the new grid lies along the well pair direction and the limit of the x-axis is the start and end point of the well. The y axis limit is defined as the width of the well polygon which is the effective area (in the xy plane) within which bitumen can be recovered by this well pair. The new z axis direction and limit is unchanged. Regridding is done as a nearest cell resampling; no upscaling (or downscaling) is performed. The purpose of regrinding is: (a) to reduce run times by eliminating data outside the area of interest (red box in Figure 3) (b) to increase the precision of the calculation by using a finer grid in the area of interest. Determining that which cells are inside the cone surface (Figure 3b) is straightforward, but calculation of the fractional area of the cells within the cone for the cells which intersect the cone surface is difficult and in the case of larger cells, this fractional area must be considered (c) calculation is easier when the reference axis lies in the direction of well pair.

5. *Calculating recoverable, lost and unrecoverable bitumen*: Recall the definition of recoverable, lost and unrecoverable resources as given in Section 1. Recoverable bitumen is the volume of bitumen which is extracted by a well pair, lost bitumen is the volume of bitumen which can't be accessed (below the production well polygon), and unrecovered bitumen is the volume which can't be extracted due to the lost well length. Lost well length is the part of the well which lies below the BCB surface.

The resource calculation is done for all the possible depths of the well, and the one with the maximum available resource is selected as optimum. In this process the location of the centre of the cell is used to determine whether this cell contributes in the production or not. The volume of recoverable, lost and unrecoverable bitumen is calculated as follows:

1. A cell below BCB surface is not considered in the calculation.
1. If the cell is located below plane A (figure 1) then it is considered lost.
2. If cell is inside the cuboid of lost well length (Figure 2b) but outside the either of the cone (shown at the end points of the lost well length), then this cell is considered unrecoverable. All cells inside the volume of the intersection of the cuboid and a cone are considered recoverable.
3. All other cells, i.e. not affected by lost well length, that lie above the BCB are considered recoverable.
4. For any cell the amount of bitumen present in this cell is calculated as follows:
    a. First the facies type of cell is checked. If it is a type of faceis which contains bitumen then only the volume of bitumen entrapped in this cell is calculated, otherwise it is assumed that there is no bitumen inside this cell.
    b. If a cell passes the above criterion then it is checked against the provided minimum porosity, maximum water saturation and minimum vertical permeability cut-offs. If this cell passes all these criteria then the volume of available bitumen inside this grid cell is:

$$V_{bitumen} = V_{cell} \bullet \phi \bullet (1 - S_w) \quad (1)$$

$V_{bitumen}$ = Volume of bitumen present inside cell
V_{cell} = Volume of cell
ϕ = Porosity value of cell
S_w = Water saturation value of cell

To check the position of a cell with relative to a cone (as in case of lost well length) the equation of the surface of a cone is used. The standard equation of cone is with vertex at $(x0, y0, z0)$ is:

$$(x - x0)^2 + (y - y0)^2 = c(z - z0)^2 \quad (2)$$

$(\mathrm{x,y,z})$ represents any point on the surface of cone. The angle of the cone (alpha on Figure 4) can be related to the parameter c . In Figure 4 the cone is shown with its vertex located at $(\mathrm{x0,y0,z0})$ and cone angle of α . Consider any point $(\mathrm{x,y,z})$ on the surface of cone. Define vectors $\vec{a}$ and $\vec{b}$ as shown in Figure 4.

$$\vec{a} = (x - x0)\,\hat{i} + (y - y0)\,\hat{j} + (z - z0)\hat{k}, \qquad b = (z - z0)\hat{k}$$

Angle α can be expressed as: $\cos(\alpha) = \frac{\vec{a} \bullet \vec{b}}{|\vec{a}||\vec{b}|}$. After some calculations and using above cone equation:

$$c = \sec^2(\alpha) - 1 \tag{3}$$

To check the position of centre $(\mathrm{x,y,z})$ of a cell inside cone surface is straight forward by checking the sign of the function $f(x,y,z) = (x - x1)^2 + (y - y1)^2 - c(z - z1)^2$. If value of the function is negative then the cell is inside the cone surface. All cells present in the cuboid are checked against two cones located at very end of all lost well lengths.

6. *Penalizing the objective function with the cost of the loss of steam in areas of lost well length*- Steam going through part of the well which is lost beneath BCB is not used in the production of bitumen, thus it adds additional cost. The aim here is to convert this additional cost in terms of bitumen volume by penalizing recoverable volume of bitumen. This cost is the function of total percentage of lost well length. The nature of this penalty is not established but a general idea is illustrated through figure-5 and equation-2. In the developed program `WellVertPos` the option of including this penalty is optional.

$$f_{obj} = V_{recoverable} * penalty \tag{4}$$

7. *Selecting optimum well elevation from realizations*- Calculation is done for wells at all many possible elevations for each and every realization. Elevation between BCB and TCB are discredited at regular intervals to determine the value of objective function at these well elevations. The well elevation with maximum recoverable resource is selected for each realization. The mean of objective function is calculated for all the well elevations and a final mean profile of production Vs well elevation is generated. An optimal well elevation is selected from this profile corresponding to the maximum recovery of bitumen. Quantification of uncertainty is done by calculating the standard deviation of the recoverable bitumen for all elevations.

8. Result

This section explains the effect of well elevation on recoverable bitumen and the effect of BCB surface on selection of well elevation. Hypothetical data has been generated to highlight the different effects of BCB surface over optimum well elevation. All realizations (some shown in figure 6) were generated randomly but following certain rules. The dimension of the volume of bitumen deposit used for this case study is: 2KM long in the x and y directions and up to 70m in the z direction. The starting center of the grid model was at (0,0,0). A grid size with 25m x 25m x 1m was used to generate the realization. First 100 realizations of BCB surface were generated. The way the BCB surface was generated was random- First random locations were selected within the 2Km x 2Km of xy-plane, at these locations random values of BCB elevation was generated, but these random values of BCB elevation was restricted between 0m and 40m. After this, The BCB surface was gridded over all x-y grids using the "Triangle based cubic interpolation". For this purpose MATLAB's `gridata()` function has been used. After generating the BCB surface, reservoir variables- facies type, porosity, water saturation and vertical permeability were generated randomly but in a controlled manner. 5 types of different facies facies- sandstone, breccia, sandy-

IHS, muddy-IHS, and mud have been considered in modelling. All these facies have been assigned integers from 5 to 1 respectively to indicate them in the numerical model. All reservoir variables were generated in such a manner that the quality of reservoir remains bad below BCB surface and quality gradually increases as moving up the BCB surface but again decreases as it reaches the top elevation of the model (70m) (Figure 6). The well co-ordinates for this example were (625m, 625m) to (1491m, 1125m). All the calculations were done with no penalization of objective function for additional cost of steam due to lost well length.

The result from 100 realizations are shown if Figure 7(a). Red dots indicate the maximum elevation of BCB surface (inside well polygon) and green dots indicate the elevation with maximum recovery of bitumen. In general it seems that the elevation with maximum BCB is the elevation for maximum recovery. But the results shown in figure-7(a) suggest that the recovery is more if we go deeper. This happens because of a very rough BCB surface. If we use a smoother BCB surface then depth of maximum recovery coincides with the maximum BCB elevation (figure-8b). Uncertainty in recoverable bitumen as function of depth is shown in figures 7(d) and 8(d) by calculating the standard deviation of recoverable bitumen from 100 realizations. In practice an elevation with good recovery and a low uncertainty should be selected to get the optimal in the sense of both production and risk. There exists a very sharp increase in the uncertainty and decrease in production after we move deeper from the elevation with maximum production. Thus going deeper from optimum elevation is not recommended. A selection of good elevation of well pair is based on the results of the model. For example in case of smooth BCB (Figure 8(d)), point A (which is located slightly above the elevation with maximum production), should be considered for well placement because there is not much difference in the production but point A has comparatively low uncertainty. A small decrease in production and relatively high decrease in risk makes point A more attractive than elevation with maximum recoverable bitumen.

9. Conclusion

The authors have proposed a simple methodology on optimum vertical well placement by checking the amount of recoverable bitumen at every elevation. Working with several realizations provides the amount of uncertainty along with recoverable bitumen. `WellVertPos` takes about 20 seconds for 1 realization for 11.2 million cells (on a computer with 64 bit, 2GHz processor and 3GB memory) to calculate amount of recoverable bitumen for 70 different elevations.

There are a number of areas of future work. Penalizing the objective function with a factor which can reflect the cost of loss of steams in the areas of lost well length is more realistic towards finding an optimum well placement. Although this factor has been implemented in the developed tool (optional), a correct relationship will be very helpful to the next step of modifications in the tool. Calibration with flow simulation could help determine a more correct relationship.

References:

Deutsch, C.V. and McLennan, J.A., Guide to SAGD (Steam Assisted Gravity Drainage) reservoir characterization Using Geostatistics (2005), Centre of Computational Geostatistics, Guidebook Series, Vol3.

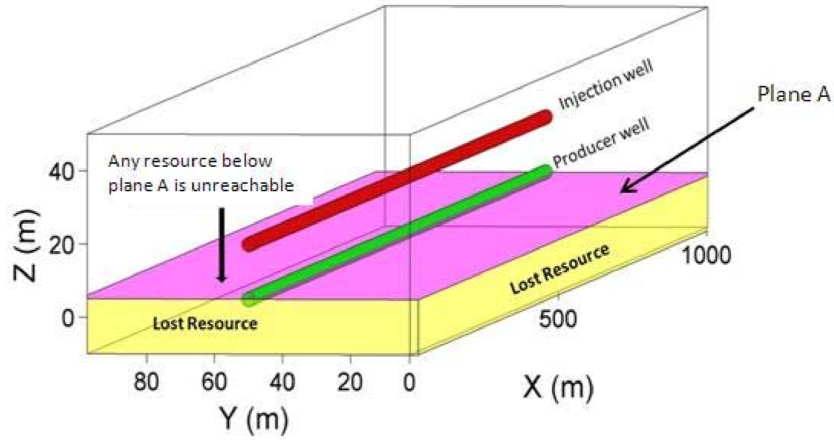


Figure 1: A well pair in SAGD. Any resource beneath producer is not accessible.

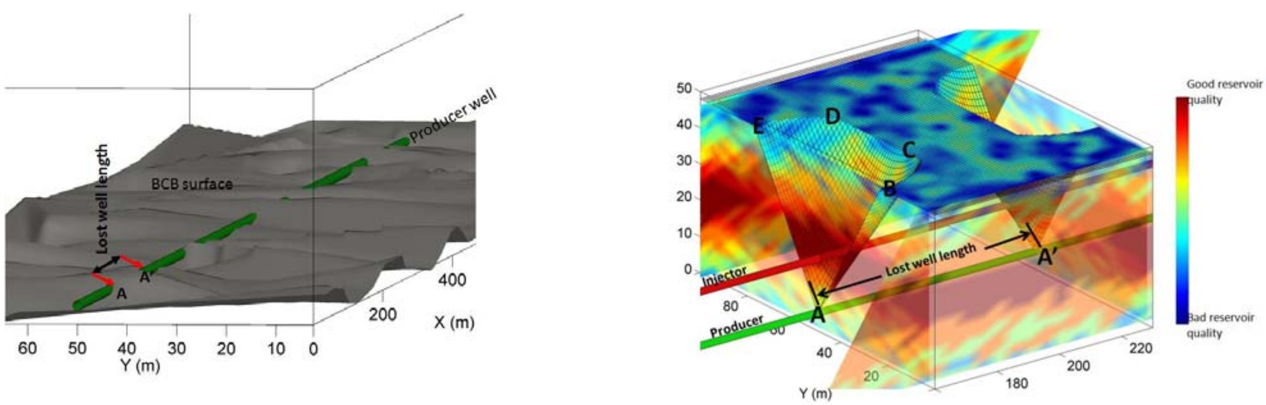


Figure 2(a)

Figure 2(b)

Figure 2: (a) Lost well length and BCB surface. Any well part below BCB surface is "lost well length". **(b)** Unrecoverable resource because of lost well length- AA' is a part of the producer well that has been lost. All the resource inside the cuboid is unrecoverable *EXCEPT* the volume between a plane perpendicular to well and a surface of half-cone. A-B-C-D-E-A is one such volume. The same type of volume exists in the opposite side at A'.

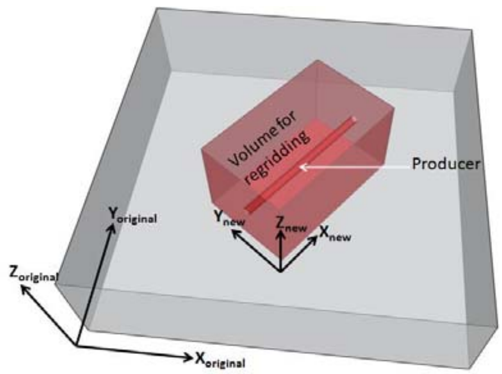


Figure 3: Regridding the original data along the well pair direction. Only data inside the smaller cuboid is included in the calculations.

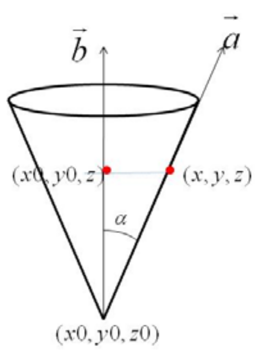


Figure 4: Determining equation of cone.

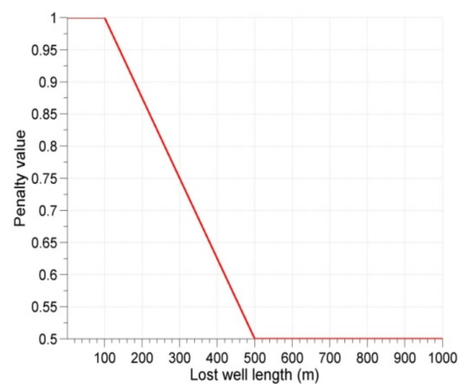


Figure 5: A penalty function for lost well length

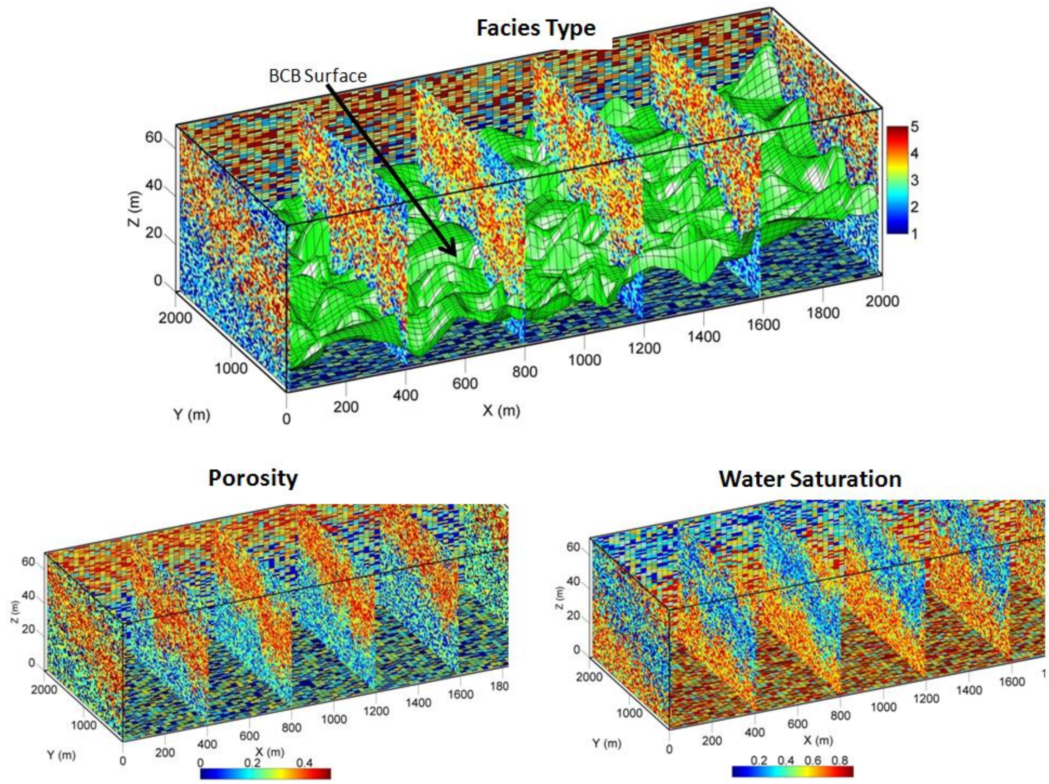


Figure 6: A 3D geological realization of reservoir variables. All data are the volume data. For illustration purposes different slices of the data is shown.

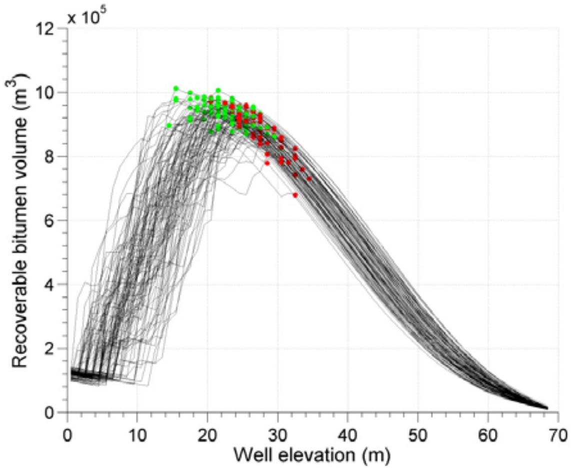


Figure 7(a)

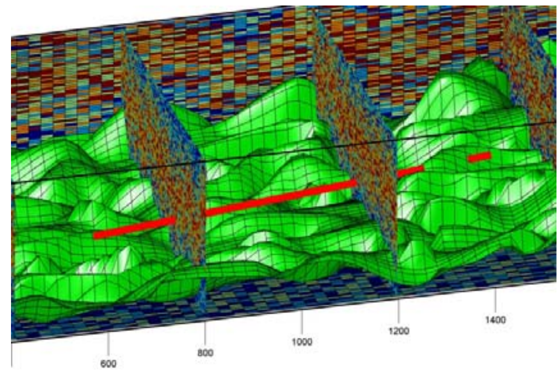


Figure 7(b)

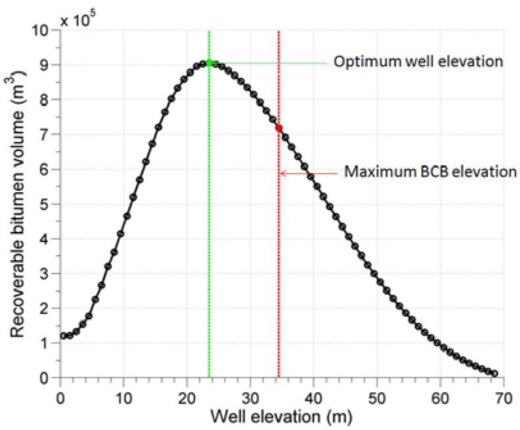


Figure 7(c)

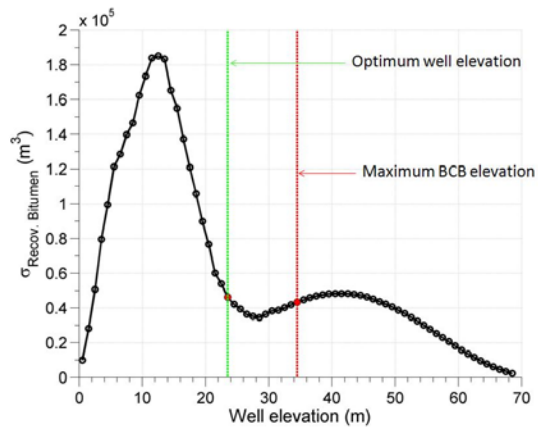
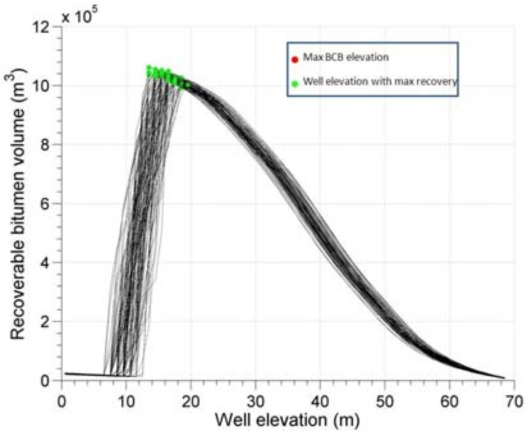


Figure 7(d)

Figure 7: Result in case of a rough BCB surface **(a)** well elevation Vs recoverable bitumen from 100 realizations, a rough BCB surface. **(b)** Realization # 1, and optimal well placement. **(c)** Optimum well elevation and maximum BCB elevation from output of realizations. **(d)** Measure of uncertainty of well depth in terms of recoverable resource.



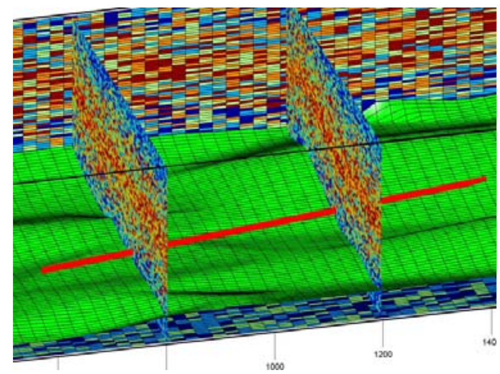
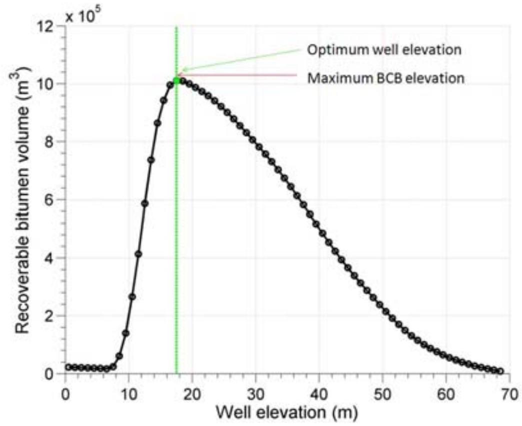


Figure 8(a) **Figure 8(b)**



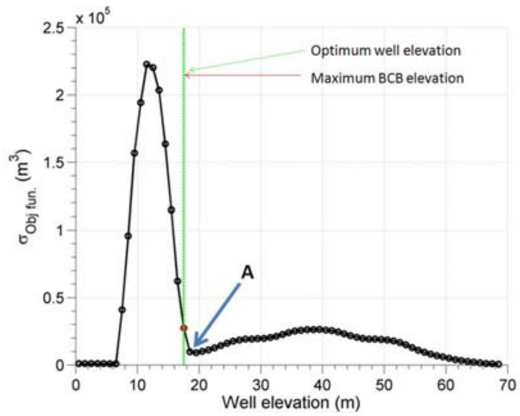


Figure 8(c) Figure 8(d)

Figure 8- Result in case of a smooth BCB surface