DEVELOPING A PYTHON ALGORITHM TO CALCULATE PRESSURE CHANGES DURING CEMENT DISPLACEMENT IN OILFIELD WELLS

József Pap
PhD student, Research Institute of Applied Earth Sciences, University of Miskolc
3515 Miskolc, Miskolc-Egyetemváros, e-mail: zed.tylor@gmail.com

Krisztián Mátyás Baracza
Director of Institute, Research Institute of Applied Earth Sciences, University of Miskolc
3515 Miskolc, Miskolc-Egyetemváros, e-mail: krisztian.baracza@uni-miskolc.hu

Zoltán Tibor Turzó
Head of Department, Institute of Mining and Energy, University of Miskolc
3515 Miskolc, Miskolc-Egyetemváros, e-mail: zoltan.turzo@uni-miskolc.hu

Abstract

Cementing is a crucial step when developing an oilfield well, which is usually done by pumping high-density slurry through the casing and then displacing it to the annular section. However, especially in deep structures, the whole process should be handled with increased care due to presence of excess hydrodynamic pressure. This may reach casing burst and collapse pressure limits, moreover formation fracture pressure limit in certain cases. This study introduces an algorithm, developed in Python, able to calculate dynamic pressure changes during cementing operations, and to alert when a critical pressure is reached at any point.

Keywords: *cementing, pressure changes, formation and casing pressure limits, Python model*

1. Introduction

The aim of any cementing operation is to separate the formation behind the casing and to ensure stability of the drilled section and the entire well structure. In addition to several design parameters, burst and collapse pressure limits of the casing should be handled with increased care. In addition with the formation pore and fracture pressure limits, the injection of high-density cement slurry results in a significantly increased pressure gradient through the wellbore (Leksir, 2020). This article introduces a Python algorithm, developed by the authors, suitable for calculating and graphically visualizing pressure changes in vertical and “J” shape (build and hold, or horizontal) wells.

2. General overview

According to ***Table 1***., we introduce a fictive well, having a previously cemented casing section with a nominal diameter: 13-3/8”, weight: 68 ppf and grade: L-80 (Weatherford, 2004). The aim is to simulate a cementing process, where the target casing (nominal diameter: 9-5/8”, nominal weight: 47 ppf, material grade: L-80) is planned to be cemented with an injection sequence with known parameters. Formation pore and fracture pressure limits are also known.

Table. 1. *Model input data*

WELL DIMENSIONS		FLUID DATA	Volume *[m³]*	Density *[kg/m³]*	Viscosity *[Pa s]*	OPERATIONAL DATA	
TVD [m]	2104	Completion fluid	143.941	1140	0.030	Pump rate [lpm]	1800
Hole D [m]	0.3112	Washer	6.0	1140	0.035	Pump eff. [%]	92.5
1. CSG1 Depth [m]	1250	Scavenger	3.0	1300	0.400	Simulation timestep [s]	10e9
1. CSG1 ID [m]	0.31534	Lead Slurry	52.4	1500	0.500	**FORMATION DATA**	
2. CSG2 Depth [m]	2104	Tail Slurry	12.3	1900	0.030	P(pore) [bar]	182
2. CSG2 ID [m]	0.2445 / 0.2205	Displacer fluid	79.8	1140	0.020	P(fracture) [bar]	365

From the dimensional parameters of the cemented previous casing and the open-hole section, the volume of the well could be easily determined from the following formula:

$$V_{WELL} = \frac{\pi}{4}\left[\, ID_{CSG2}^2 L_{WELL} + (OD_{CSG2}^2 - D_{HOLE}^2) L_{OH} + (OD_{CSG2}^2 - ID_{CSG1}^2) L_{CH}\,\right] \tag{1}$$

Prior to the cementing operation, the well is filled with homogenous well completion fluid. In this case, the static bottom-hole pressure is equivalent to the hydrostatic pressure of the fluid column:

$$P_{BOTTOM} = \sum(\rho_{FLUID}\, g\, h_{FLUID}), \tag{2}$$

For multiple fluids in the well, the height of the individual fluid components can be calculated in the target casing or the annular section (Rabia, 2002):

$$h_{FLUID\ IN\ STRING} = \frac{V_{FLUID}}{ID_{CSG2}^2}\frac{4}{\pi} \tag{3}$$

$$h_{FLUID\ IN\ OH\ ANNULAR} = \frac{V_{FLUID}}{(D_{HOLE}^2 - OD_{CSG2}^2)}\frac{4}{\pi} \tag{4}$$

$$h_{FLUID\ IN\ CH\ ANNULAR} = \frac{V_{FLUID}}{(ID_{CSG1}^2 - OD_{CSG2}^2)}\frac{4}{\pi} \tag{5}$$

It is important to note that formulae (3-5.) are only valid for vertical wells. For deviated wells, individual component heights will be lengths instead. Here, component hydrostatic pressure is dependent on the top and bottom position in the given trajectory at any simulation timestep. This article introduces calculations for regular “J”-shaped (build and hold type) well trajectory, where the well path consists of a vertical, an arc (build), and an inclined (hold) section. This has to be described with additional parameters: bottom-hole true vertical depth (TVD), kick-off point (KOP), build-up rate (BUR), and horizontal distance from the surface (HD). To determine the total measured depth, we need to calculate the radius of curvature (Krishnan and Kulkarni, 2016):

$$R = \frac{180 * 30}{BUR\pi} \tag{6}$$

Arc endpoint inclination (α) is calculated from:

$$X = tan^{-1} \frac{HD-R}{TVD-KOP} \quad (7)$$

$$OT = \frac{HD-R}{\sin(x)} \quad (8)$$

$$Y = sin^{-1} \frac{R}{OT} \quad (9)$$

$$\alpha = X + Y \quad (10)$$

Then, we get the length from the arc and the tangential (hold) section from:

$$ARC = \frac{\alpha 2\pi R}{360} \quad (11)$$

$$HOLD = \frac{R}{\tan(Y)} \quad (12)$$

The total measure depth of the well will be:

$$MD = KOP + ARC + HOLD \quad (13)$$

Knowing the pumping rate and pump efficiency, the bottom MD position of each fluid component can be calculated at any time. In vertical wells, MD=TVD, therefore, accumulated pressure can be easily calculated, using formula (2). To get the top and bottom TVD positions of each fluid component in “J”-shaped deviated wells, therefore, to calculate individual fluid hydrostatic pressures, we need to determine component bottom TVD, based on the following table (Guan et al., 2021):

Table. 2. *Calculation of true vertical depth (TVD_F), horizontal distance (HD_F) and inclination (α) of the component at bottom measured depth (MD_F)*

MD_F	TVD_F	HD_F	α_F
$MD_F \leq KOP$	MD_F	0	0
$KOP < MD_F \leq KOP+ARC$	$\sin\left(\frac{MD_F KOP}{ARC * \alpha}\right) * R + KOP$	$R - \cos\left(\frac{MD_F KOP}{ARC * \alpha}\right) * R$	$\frac{MD_F KOP}{ARC * \alpha}$
$KOP+ARC < MD_F \leq MD$	$\cos(\alpha) * (MD_F - ARC - KOP) + KOP + TVD_{ARC}$	$\sin(\alpha) * (MD_F - ARC - KOP) + Y_{ARC}$	α

While it is assumed, that with a constant pump rate, bottom hole pressure changes linearly, calculation of the fluid positions is mandatory each time, when one of the following events occurs:

- A component is injected into the well, i.e. switching to the next fluid
- A component reached the well bottom: the slope of the pressure curve changes on the annular side
- A component reached the previous cemented casing shoe: the flow cross-section changes, so the slope of the pressure curve changes
- A component reached the top: the previous fluid leaves the well and the slope of the pressure curve changes on the annular side

3. Algorithm introduction

The algorithm was developed in Python, which can be run directly from the command line or a GUI after compilation. Once invoked, the program initializes a result matrix:

$$\begin{matrix} \boldsymbol{H_{IN}} & \boldsymbol{H_{STR}} & \boldsymbol{H_{OH}} & \boldsymbol{H_{CH}} & \boldsymbol{H_{OUT}} & \boldsymbol{\rho_F} & \boldsymbol{P_{IN}} & \boldsymbol{P_{OUT}} \\ F_{[0,0]} & F_{[0,1]} & F_{[0,2]} & F_{[0,3]} & F_{[0,4]} & F_{[0,5]} & F_{[0,6]} & F_{[0,7]} \\ F_{[1,0]} & F_{[1,1]} & F_{[1,2]} & F_{[1,3]} & F_{[1,4]} & F_{[1,5]} & F_{[1,6]} & F_{[1,7]} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ F_{[n,0]} & F_{[n,1]} & F_{[n,2]} & F_{[n,3]} & F_{[n,4]} & F_{[n,5]} & F_{[n,6]} & F_{[n,7]} \end{matrix}$$

where H_{IN} is the to-be injected component height, H_{STR}, H_{OH}, H_{CH} are component heights in string, open hole, and cased hole annulus, respectively. H_{OUT} is the height of the fluid leaving the wellbore, ρ_F is component density, and P_{IN} and P_{OUT} are component hydrostatic pressures. The last *(n^{th})* component is reserved for the well completion fluid in the wellbore. Before model initialization, the algorithm reads the input file, containing model data, then handles the following exceptions:

Exceptions handled prior to initialization:

- Missing input data
- Input data with zero or negative values (excluding excess volume calculated in the open hole)
- Empty or incomplete sequence list
- Incorrect diameter data (pipe diameter greater than hole diameter)
- Incorrect position of previous pipe string (deeper than drilled length)
- Pump efficiency greater than 100%

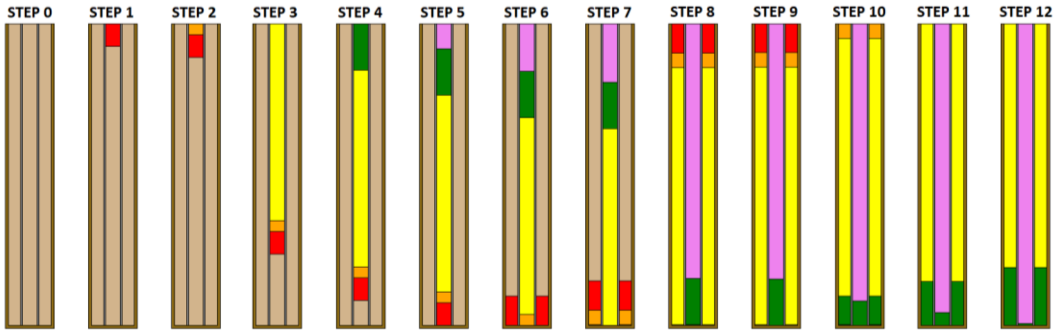
Exceptions handled between each timestep:

- Bottom hole pressure below the pore pressure of the formation
- Bottom hole pressure above the formation fracture pressure limit
- Bottom hole pressure above the casing burst pressure
- Bottom hole pressure above the casing collapse pressure limit

Any of the exceptions above raises an error message, with an indication on the user interface. The successfully initialized result matrix, according to data in ***Table 1.***:

COMPONENT NAME	H_{IN}	H_{STR}	H_{OH}	H_{CH}	H_{OUT}	RHO_F	P_{IN}	P_{OUT}
Chemical wash	157.125	0	0	0	0	1.14	0	0
Scavenger	78.562	0	0	0	0	1.30	0	0
Lead Slurry	1372.221	0	0	0	0	1.50	0	0
Tail Slurry	322.105	0	0	0	0	1.90	0	0
Displacer Fluid	2089.757	0	0	0	0	1.14	0	0
Completion Fluid	0	2104	854	1250	0	1.14	235.299	235.299

The calculation is finished when we have eliminated each value from the H_{IN} column. Therefore, the algorithm checks the first non-zero value. If any of the events mentioned above occur during the calculation, then only a portion of the fluid height is added to the next column. The sum of H_{STR}, H_{OH},, and H_{CH} columns must be equal with the given well dimensions at any timestep. When height values are moved between H_{STR}-H_{OH} or H_{OH}-H_{CH}, those values must be multiplied by the area proportion of the given sections. From individual fluid heights, we finally get individual pressures in the casing (P_{IN}) and in the annular section (P_{OUT}) where the sum of each column gives the bottom hole pressure. Corresponding with the cumulated pump time of the pressures, the result plot can be drawn. Simulation steps for a simplified well structure (without the previous casing section) are described in the following figure:



INDIVIDUAL FLUID HEIGHTS *[m]*

	STEP 0 STR	STEP 0 ANN	STEP 1 STR	STEP 1 ANN	STEP 2 STR	STEP 2 ANN	STEP 3 STR	STEP 3 ANN	STEP 4 STR	STEP 4 ANN	STEP 5 STR	STEP 5 ANN	STEP 6 STR	STEP 6 ANN	STEP 7 STR	STEP 7 ANN	STEP 8 STR	STEP 8 ANN	STEP 9 STR	STEP 9 ANN	STEP 10 STR	STEP 10 ANN	STEP 11 STR	STEP 11 ANN	STEP 12 STR	STEP 12 ANN
Chemical Wash			157.12		157.12		157.12		157.12		157.12			206.11		206.11		206.11		200.93						
Scavenger					78.56		78.56		78.56		78.56		78.56			103.05		103.05		103.05		103.05				
Lead Slurry							1372.22		1372.22		1372.22		1372.22		1372.22		3.94	1794.84		1800.01		1800.01		1800.01		1700.16
Tail Slurry									322.11		322.11		322.11		322.11		322.11		322.11		168.92	200.93	90.36	303.99	14.24	403.84
Displacer Fluid											173.99		331.11		409.67		1777.95		1781.89		1935.08		2103.64		2089.76	
Well Fluid	2104.00	2104.00	1946.88	2104.00	1868.31	2104.00	496.09	2104.00	173.99	2104.00		2104.00		1897.89		1794.84										

INDIVIDUAL FLUID PRESSURES *[bar]*

	STEP 0 STR	STEP 0 ANN	STEP 1 STR	STEP 1 ANN	STEP 2 STR	STEP 2 ANN	STEP 3 STR	STEP 3 ANN	STEP 4 STR	STEP 4 ANN	STEP 5 STR	STEP 5 ANN	STEP 6 STR	STEP 6 ANN	STEP 7 STR	STEP 7 ANN	STEP 8 STR	STEP 8 ANN	STEP 9 STR	STEP 9 ANN	STEP 10 STR	STEP 10 ANN	STEP 11 STR	STEP 11 ANN	STEP 12 STR	STEP 12 ANN
Chemical Wash			17.57		17.57		17.57		17.57		17.57			23.05		23.05		23.05		22.47						
Scavenger					10.02		10.02		10.02		10.02		10.02			13.14		13.14		13.14		13.14				
Lead Slurry							201.92		201.92		201.92		201.92		201.92		0.58	264.11		264.87		264.87		264.87		250.18
Tail Slurry									60.04		60.04		60.04		60.04		60.04		60.04		31.49	37.45	16.84	56.66	2.65	75.27
Displacer Fluid											19.46		37.03		45.82		198.84		199.28		216.41		225.19		233.71	
Well Fluid	235.3	235.3	217.73	235.3	208.94	235.3	55.48	235.3	19.46	235.3		235.3		212.25		200.72										

INDIVIDUAL FLUID PUMP TIMES *[s]*

	STEP 0 STR	STEP 0 ANN	STEP 1 STR	STEP 1 ANN	STEP 2 STR	STEP 2 ANN	STEP 3 STR	STEP 3 ANN	STEP 4 STR	STEP 4 ANN	STEP 5 STR	STEP 5 ANN	STEP 6 STR	STEP 6 ANN	STEP 7 STR	STEP 7 ANN	STEP 8 STR	STEP 8 ANN	STEP 9 STR	STEP 9 ANN	STEP 10 STR	STEP 10 ANN	STEP 11 STR	STEP 11 ANN	STEP 12 STR	STEP 12 ANN
Chemical Wash			180		180		180		180		180			180		180		180		180		180		180		180
Scavenger					90		90		90		90		90			90		90		90		90		90		90
Lead Slurry							1572.13		1572.13		1572.13		1572.13		1572.13		5.67	1566.46		1572.13		1572.13		1572.13		1572.13
Tail Slurry									369.03		369.03		369.03		369.03		369.03		369.03		193.10	175.89	103.99	265.88	16.85	352.11
Displacer Fluid											118.84		298.84		388.84		1955.61		1960.99		2136.91		2226.92		2394.17	
Well Fluid																										

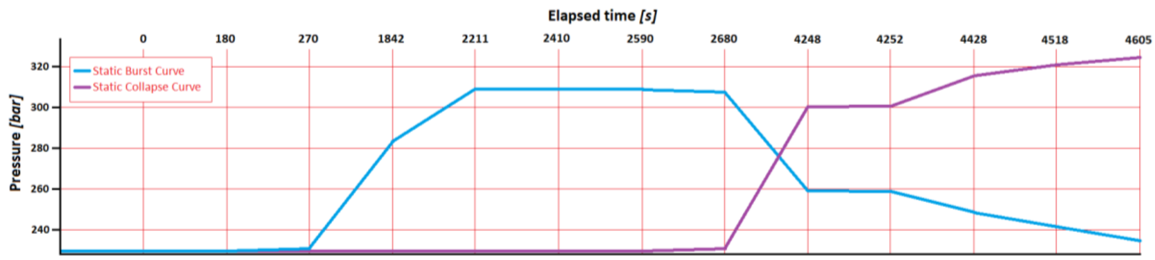


Figure 1. B*ottomhole pressure calculation in the casing and annular section for each simulation timestep. From the cumulated pressure and total pumping time at each step, the result plot can be drawn.*

In this example, total well volume is 153.5 m^3, meaning that the washer and the scavenger fluid leaves through the annulus upon finishing the cementing operation, while an additional 14.24 m tail slurry is left in the casing bottom, which means we can approximate the top position of the cement plug, before we drill it through. The result, provided by the algorithm is introduced in the following plot, identical to the results, illustrated on ***Figure 1.***:

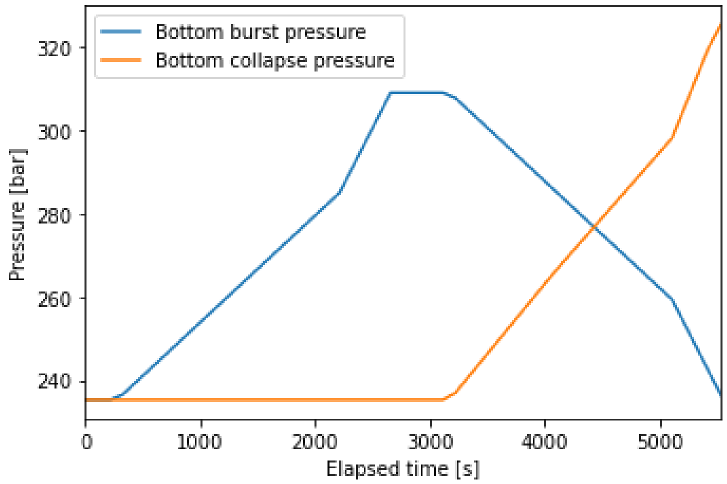


Figure 2. *Bottomhole pressure through cement displacement. Bottom hydrostatic pressure before WOC (Wait on Cement) is 236.36 bar in string and 325.45 bar in the annulus.*

The algorithm to calculate components of "J"-trajectories is compiled into a separate executable file, which is called upon selecting the profile from the user interface. In that case, several other exceptions needed to be handled (missing or negative values of additional required inputs). The initialized result matrix for deviated wells contains several additional columns: apart from length (*L*) and height (*H*) of components in each section, fluid top positions (*S*) and bottom positions (*E*) are calculated, based on ***Table 2.***, therefore pressure of the components (*P*) can be calculated:

L_{IN}	H_{STR}	L_{STR}	H_{OH}	L_{OH}	H_{CH}	L_{CH}	ρ_F	P_{STR}	P_{OH}	P_{CH}	S_{STR}	E_{STR}	S_{OH}	E_{OH}	S_{CH}	E_{CH}
$F_{[0,0]}$	$F_{[0,1]}$	$F_{[0,2]}$	$F_{[0,3]}$	$F_{[0,4]}$	$F_{[0,5]}$	$F_{[0,6]}$	$F_{[0,7]}$	$F_{[0,8]}$	$F_{[0,9]}$	$F_{[0,10]}$	$F_{[0,11]}$	$F_{[0,12]}$	$F_{[0,13]}$	$F_{[0,14]}$	$F_{[0,15]}$	$F_{[0,16]}$
$F_{[1,0]}$	$F_{[1,1]}$	$F_{[1,2]}$	$F_{[1,3]}$	$F_{[1,4]}$	$F_{[1,5]}$	$F_{[1,6]}$	$F_{[1,7]}$	$F_{[1,8]}$	$F_{[1,9]}$	$F_{[1,10]}$	$F_{[1,11]}$	$F_{[1,12]}$	$F_{[1,13]}$	$F_{[1,14]}$	$F_{[1,15]}$	$F_{[1,16]}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$F_{[n,0]}$	$F_{[n,1]}$	$F_{[n,2]}$	$F_{[n,3\}}$	$F_{[n,4]}$	$F_{[n,5]}$	$F_{[n,6]}$	$F_{[n,7]}$	$F_{[n,8]}$	$F_{[n,9]}$	$F_{[n,10]}$	$F_{[n,11]}$	$F_{[n,12]}$	$F_{[n,13]}$	$F_{[n,14]}$	$F_{[n,15]}$	$F_{[n,16]}$

We validated the solver by setting KOP, HD, and BUR to zero. In that case, the simulator finished in 16 steps and component lengths were equal to their height values:

	L_W	H_STR	L_STR	H_OH	L_OH	H_CH	L_CH	RHO	P_STR	P_OH	P_CH	S_STR	E_STR	S_OH	E_OH	S_CH	E_CH
Chemical Wash	0.0	0	0.0	0	0.0	0	0.0	1.14	0.0	0.0	0.0	0	0	0	0	0	0
Scavenger	0.0	0	0.0	0	0.0	0	0.0	1.3	0.0	0.0	0.0	0	0	0	0	0	0
Lead Slurry	0.0	0	0.0	450.161	450.161	1250.0	1250.0	1.5	0.0	66.241	183.938	0	0	1250.0	1700.161	0.0	1250.0
Tail Slurry	0.0	14.243	14.243	403.839	403.839	0	0	1.9	2.655	75.272	0.0	2089.757	2104.0	1700.161	2104.0	0	0
Displacer	0.0	2089.757	2089.757	0	0	0	0	1.14	233.706	0.0	0.0	0	2089.757	0	0	0	0
Well Fluid	0	0	0.0	0	0.0	0	0.0	1.14	0.0	0.0	0.0	0	0	0	0	0	0

Figure 3. *Final timestep of the original well structure, solved by the algorithm for „J"-shaped wells.*

By setting KOP to 1000 *[m]*, HD to 2000 *[m]* and BUR to 2 *[°/30m]*, the simulator finished in 8 steps. In that case, cumulative L_{STR} gives total measured depth, while pressure of each component is calculated from the difference of their bottom and top values.

	L_W	H_STR	L_STR	H_OH	L_OH	H_CH	L_CH	RHO	P_STR	P_OH	P_CH	S_STR	E_STR	S_OH	E_OH	S_CH	E_CH
Displacer	0.0	1820.34	2089.757	0	0	0	0	1.14	203.576	0.0	0.0	0	2089.757	0	0	0	0
Chemical Wash	0.0	0	0.0	40.33	206.108	0	0	1.14	0.0	4.51	0.0	0	0	2853.509	3059.617	0	0
Scavenger	0.0	0	0.0	20.17	103.054	0	0	1.3	0.0	2.572	0.0	0	0	3059.617	3162.671	0	0
Lead Slurry	0.0	215.94	1103.415	69.01	352.607	0	0	1.5	31.776	10.155	0.0	2411.863	3515.278	3162.671	3515.278	0	0
Tail Slurry	0.0	67.72	322.105	0	0	0	0	1.9	12.622	0.0	0.0	2089.757	2411.863	0	0	0	0
Well Fluid	0	0	0.0	728.0	1603.509	1246.49	1250.0	1.14	0.0	81.415	139.4	0	0	1250.0	2853.509	0.0	1250.0

Figure 4. *Final timestep results of custom well trajectory, where L_W is the calculated length of the to-be injected fluid component. STR, OH and CH represents values of string, open-hole and cased-hole (H: height, L: length, S: top position, E: bottom position, P: pressure).*

4. Graphical user interface

The user interface controls the introduced algorithms. Additionally, it is able to import any input file, and export reports. It contains a top menu, a side menu with the option to select additional cementing methods, all relevant input fields, a terminal, and a canvas visualizing the well. Result matrices are stored in the output file and once the simulation is completed, well plot for all steps can be looped with navigation buttons. If simulation of a deviated well is selected, we can pick different plot views. Once the mouse is hoovered to any of the visualized component, a tooltip window is raised, containing additional information.

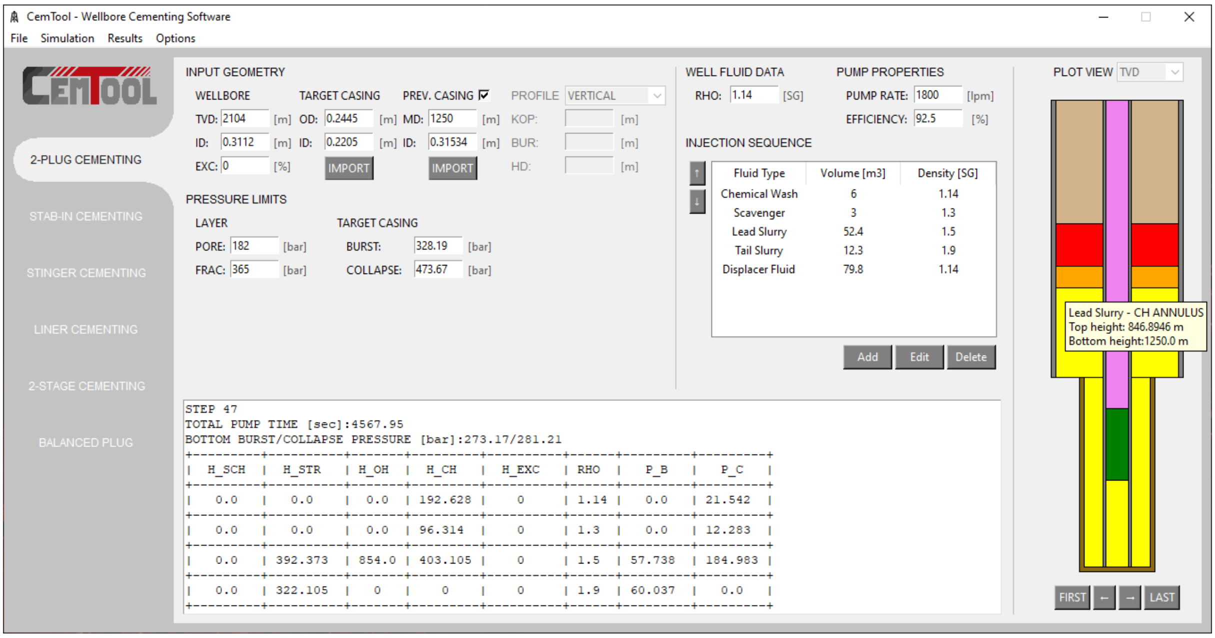


Figure 5. *User interface, containing feedback of a terminated simulation, due to hydrostatic pressure in the casing exceeded burst pressure limit of the selected casing.*

The interface contains data of more than 900 standard casing, with several sizes, material grades and thread types. According to the input, the burst pressure limit of the selected casing is 328.19 bar, while collapse pressure limit being 473.67 bar which means, that the simulation run successfully. To test exception handling, we manually reduced burst pressure limit below 300 bar. In that case, the simulation terminated with the error message below:

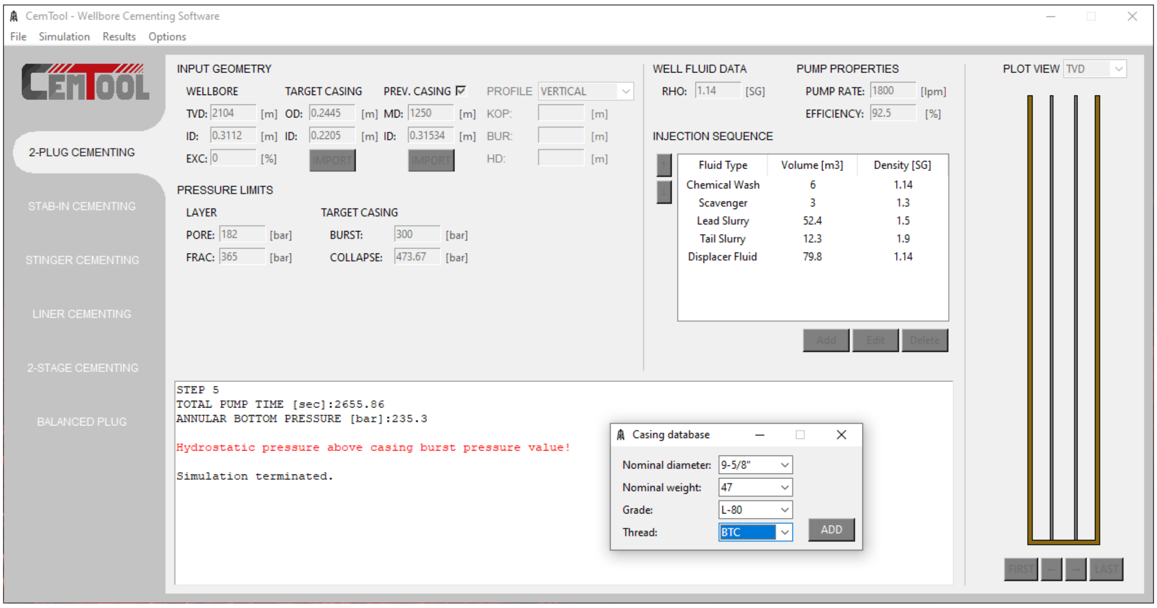


Figure 6. *User interface, containing feedback of a terminated simulation, due to hydrostatic pressure in the casing exceeded burst pressure limit of the selected casing.*

Under results, pressure plots can be viewed and saved and, in the options menu, timestep control, and a selection between metric or imperial units are provided.

5. Further development

The introduced algorithms can calculate pressure changes during cement injection and displacement, provided results are only valid for static conditions. Frictional pressure drop calculations must be included in each solver (Guo, 2021), where the biggest challenge is to estimate pressure drop in the annular region, especially in the open hole section. In the next steps, we are aiming to build functions of several rheological models into the solvers and connect it with the extended user interface.

The presented version of the software handles vertical, and "J"-shaped structures, so we focus to implement additional trajectories (build-hold-drop, multi-targeted-build, custom well based on survey data) into the main package.

6. Acknowledgements

The research was carried out in the framework of the GINOP-2.3.2-15-2016- 00010 "Development of enhanced engineering methods with the aim at utilization of subterranean energy resources" project of the Research Institute of Applied Earth Sciences of the University of Miskolc in the framework of the

Széchenyi 2020 Plan, funded by the European Union, co-financed by the European Structural and Investment Funds.

References

[1] Leksir, A. (2020). Maximum allowable pressure during heavy slurry displacement. *Journal of Petroleum Exploration and Production Technology, 10,* 2829–2844. **https://doi.org/10.1007/s13202-020-00959-5**

[2] Guo, B. (2021). Applied well cementing engineering. Chapter 6: *Cementing Hydraulics* (pp. 253-290). **https://doi.org/10.1016/B978-0-12-821956-0.00003-1**

[3] Rabia, H. (2002). *Well engineering and construction*. (pp. 157-180).

[4] Weatherford Canada DIS Group (2002). Pipe Data Handbook (pp. 1-54).

[5] Krishnan, A., & Kulkarni, A. (2016). Well trajectory survey of a directional well. *International Research Journal of Engineering and technology (IRJET)*, 3, 1418–1423.

[6] Guan, Z., Chen, T., & Liao, H. (2021). *Theory and technology of drilling engineering*. Springer, pp. 295-302. **https://doi.org/10.1007/978-981-15-9327-7**