

Memo

Estimation of Relation between Seismic Moment Magnitudes and Hypothetical Salt Falls



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Simplified Estimation of the Relation between Seismic Moment Magnitudes and Hypothetical Salt Falls

AkzoNobel asked DEEP/KBB for a simplified estimation of the relation of hypothetical salt falls and corresponding resulting seismic magnitudes.

Based on preset values for the seismic moment magnitude M_w the corresponding hypothetical causing salt block sizes, respectively masses were estimated.

The following agreed assumptions were made to consider hypothetical salt falls at the caverns HL-K and HL-H:

- Cavern HL-K totally filled with nitrogen
- Cavern HL-H totally filled with fully saturated brine
- Conservative approach, which means:
 - o Impact with consolidated/solid ground (i.e. no sump consideration for cavern HL-K)
 - o Vertical incidence (i.e. no consideration of "bounce back" at cavern's walls)
 - o Constant force of gravity (i.e. neglecting the reduction in the acceleration of gravity due to being inside the earth (earth's crust))
 - o No consideration of energy losses (i.e. the entire calculated kinetic energy is considered to be converted completely into seismic strain energy)
- Salt blocks of cube shape with corresponding constant drag coefficient
- Consideration of Newtonian Friction Forces only (neglecting Stokes Friction)

Furthermore, the following parameters were assumed:

- Heights of caverns: 500 m (HL-K) and 600 m (HL-H)
- Density of brine: 1,200 kg/m³
- Density of mass of rock salt: 2,200 kg/m³
- Assumed pressure at cavern HL-K: 182 bar
- Assumed temperature at cavern HL-K: 55°C
- Resulting density of nitrogen (at cavern HL-K): 175.93 kg/m³

Project No.:	5238-881618	Date:	27.02.2018
File:	180227_Memorandum_Estimation_of_Relation_Moment-Magnitudes_and_Salt_Block_Sizes_Rev00.docx		

Memo

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The following procedure was applied to calculate the salt block sizes and masses that hypothetically would cause preset seismic moment magnitudes:

- a) Calculation of the corresponding seismic strain energy E_s for the preset magnitude values as per:

$$E_s = 10^{1.5 \cdot M_w + 4.8}$$

- b) Calculation of the related Seismic Moment M_0 as per:

$$M_0 = E_s * 20\,000$$

- c) Calculation of related TNT equivalents as per:

$$4.2 * 10^{12} \text{ Joule} = 1 \text{ kg of TNT}$$

- d) Calculation of fitting size/volume of the salt block cube by using:

$$(1) \quad v_{max} = \sqrt{\frac{2 \cdot m \cdot g}{C_w \cdot \rho_{fl} \cdot A}}$$

$$(2) \quad E_s = E_{kin} = \frac{1}{2} * m * v_{max}^2$$

with

v_{max} = max. achievable velocity

m = mass of rock salt

g = acceleration of gravity

C_w = drag coefficient

ρ_{fl} = density of the fluid (gas/brine)

A = cross section area of the salt block/cube

E_{kin} = kinetic Energy

- e) Calculation of corresponding distance h , where the max. speed is achieved as per:

$$h = \frac{v_{max}^2}{2 * g}$$

- f) Determination of the corresponding rock salt mass

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Memo

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The principle of the simplified calculations is shown in Figure 1.

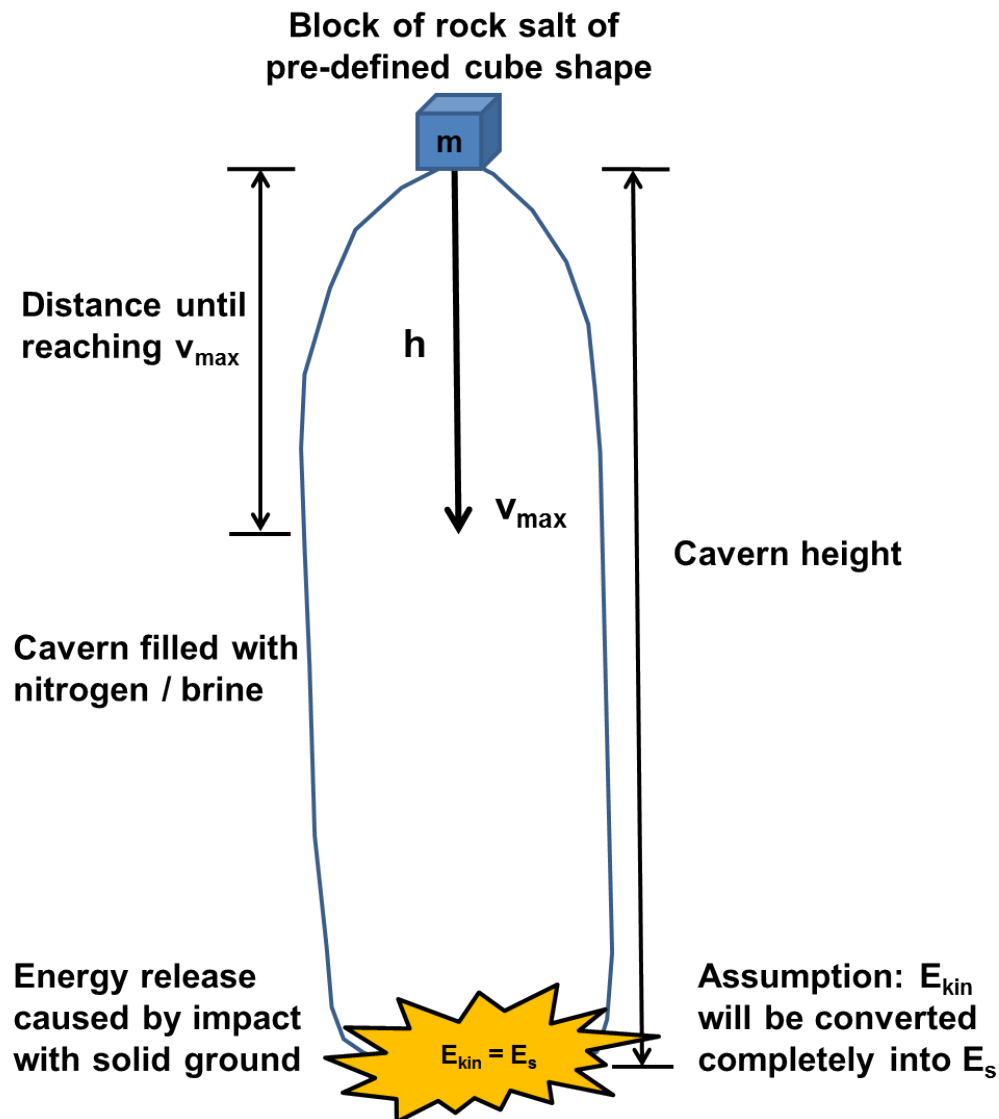


Figure 1: Principle of the simplified hypothetical salt fall

The drag (for nitrogen) and the friction (in brine) counteract the acceleration of gravity. At a specific distance h the acceleration is totally compensated by the drag/friction. Thence, the blocks fall with a constant velocity $v_{\max}$. That means that the maximum achievable velocity of a falling salt block is independent of the cavern height, provided that the cavern height is larger than the distance h . However, the distance for reaching the maximum velocity is dependent on the salt block and the fluid in the cavern as per d) and e).

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Memo

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Case Study – Scenarios

To get an impression of the hypothetical rock salt masses that would cause seismic moment magnitudes M_w of -0.5 to 2.0, a case study was performed considering cubic salt blocks falling in nitrogen (cavern HL-K) and brine (cavern HL-H) that release a kinetic energy E_{kin} in the amount of the M_w -related seismic strain energy E_s :

Additionally, for the preset moment magnitude of $M_w = 1.0$ the cube-related drag coefficient of $C_w = 1.0$ was varied (0.5 and 1.5) to get an idea of the relation between drag coefficient and resulting rock salt masses. Actually, a drag coefficient C_w of 0.5 and 1.5 do not belong to geometrical cube shapes. But for this simplified estimation the cube shape was kept.

The results of the above mentioned case study scenarios are shown in Table 1 for the hypothetical salt falls in nitrogen and in Table 2 for the corresponding salt falls in brine.

Table 1: Results of the hypothetically assumed salt falls at cavern HL-K (nitrogen)

Parameter	Dimension	Case 1	Case 2	Case 3	Case 4-0	Case 4-1	Case 4-2	Case 5	Case 6
Moment Magnitude M_w	-	-0.5	0.0	0.5	1.0	1.0	1.0	1.5	2.0
Related Seismic Strain Energy E_s	10^6 Joule	0.0112	0.0631	0.3548	1.9953	1.9953	1.9953	11.2202	63.0957
TNT Equivalent of E_s	kg	0.0027	0.0150	0.0845	0.4751	0.4751	0.4751	2.6715	15.0228
Corresponding Seismic Moment M_0	10^9 Joule	0.2244	1.2619	7.0963	39.9052	39.9052	39.9052	224.4037	1261.9147
TNT Equivalent of M_0	kg	53.43	300.46	1,689.59	9,501.25	9,501.25	9,501.25	53,429.45	300,455.88
Shape of causing Salt Block	-	Cube	Cube	Cube	Cube	Cube	Cube	Cube	Cube
Drag Coefficient C_w	-	1.0	1.0	1.0	1.0	0.5	1.5	1.0	1.0
Edge Length a	m	0.45	0.70	1.07	1.65	1.39	1.82	2.54	3.91
Max. Cross Section Area A	m^2	0.20	0.48	1.15	2.72	1.92	3.33	6.45	15.29
Max. achievable Velocity v_{max}	m/s	10.53	13.06	16.21	20.11	26.08	17.28	24.96	30.97
	km/h	37.89	47.02	58.35	72.41	93.90	62.20	89.86	111.51
Distance for reaching v_{max}	m	5.65	8.70	13.39	20.62	34.68	15.21	31.75	48.90
Volume V of causing Salt Block	m^3	0.09	0.34	1.23	4.48	2.67	6.08	16.37	59.79
Resulting Mass m	kg	202.55	739.68	2,701.11	9,863.74	5,865.02	13,369.35	36,019.84	131,535.15
	t	0.20	0.74	2.70	9.86	5.87	13.37	36.02	131.54

Table 2: Results of the hypothetically assumed salt falls at cavern HL-H (brine)

Parameter	Dimension	Case 7	Case 8	Case 9	Case 10-0	Case 10-1	Case 10-2	Case 11	Case 12
Moment Magnitude M_w	-	-0.5	0.0	0.5	1.0	1.0	1.0	1.5	2.0
Related Seismic Strain Energy E_s	10^6 Joule	0.0112	0.0631	0.3548	1.9953	1.9953	1.9953	11.2202	63.0957
TNT Equivalent of E_s	kg	0.0027	0.0150	0.0845	0.4751	0.4751	0.4751	2.6715	15.0228
Corresponding Seismic Moment M_0	10^9 Joule	0.2244	1.2619	7.0963	39.9052	39.9052	39.9052	224.4037	1261.9147
TNT Equivalent of M_0	kg	53.43	300.46	1,689.59	9,501.25	9,501.25	9,501.25	53,429.45	300,455.88
Shape of causing Salt Block	-	Cube	Cube	Cube	Cube	Cube	Cube	Cube	Cube
Drag Coefficient C_w	-	1.0	1.0	1.0	1.0	0.5	1.5	1.0	1.0
Edge Length a	m	0.73	1.12	1.73	2.66	2.24	2.95	4.10	6.32
Max. Cross Section Area A	m^2	0.53	1.26	2.99	7.10	5.02	8.70	16.84	39.93
Max. achievable Velocity v_{max}	m/s	5.12	6.36	7.89	9.79	12.70	8.41	12.15	15.08
	km/h	18.44	22.89	28.40	35.25	45.71	30.27	43.74	54.28
Distance for reaching v_{max}	m	1.34	2.06	3.17	4.89	8.22	3.60	7.52	11.59
Volume V of causing Salt Block	m^3	0.39	1.42	5.18	18.92	11.25	25.65	69.10	252.35
Resulting Mass m	kg	854.91	3,121.93	11,400.47	41,631.57	24,754.28	56,427.56	152,027.74	555,165.97
	t	0.85	3.12	11.40	41.63	24.75	56.43	152.03	555.17

Memo

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Discussion of the Results

All calculated salt block masses are results of a simplified calculation for a rough estimate of the potential kinetic energy release caused by hypothetical salt falls at caverns HL-K and HL-H. The corresponding released kinetic energies are considered to be converted completely into seismic strain energies.

Based on the above mentioned assumptions the causing salt block masses falling in brine are approx. 4.22 times higher compared to the corresponding salt falls in nitrogen. For example, to cause the considered maximum moment magnitude of $M_w = 2.0$, a cubic salt block with a related mass of approx. 132 t would be necessary for a salt fall in nitrogen (see Case-6). The mass of a salt block falling in brine causing the same magnitude of $M_w = 2.0$ would be approx. 555 t (see Case-12).

The variation of the drag coefficient (see Cases 4-0 to 4-2 and Case 10-0 to 10-2) shows that the impact of the drag coefficient on the resulting rock salt masses is not negligible.

Anyway, because of the simplifying assumptions the results have to be considered as conservative. The most conservative assumption is most likely the assumption of a complete conversion of the calculated kinetic energies into seismic strain energies. In reality, "energy losses" occur for example due to the deformation/breaking of the salt blocks. Furthermore, the sump in cavern HL-K would have an attenuating effect on the impact of the salt blocks. Therefore, mainly due to these both simplifications the real salt masses can be assumed to be higher than the calculated ones.

Signed Uwe Hehmann
UH

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