# Damage Potential of Swedish GMRS to NPP RC Structures

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Presentation prepared by Vattenfall and OKG

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# Cumulative Absolute Velocity

- The CAV parameter was studied in EPRI Report NP-5930, “A Criterion for Determining Exceedance of the Operating Basis Earthquake”, July 1988, as a measure of the damage potential of earthquake ground motion.
- The computational procedure for determination of a CAV value associated with a given earthquake acceleration record was standardized in EPRI Report TR-100082, “Standardization of the Cumulative Absolute Velocity”, December, 1991
- The CAV is the integral of the absolute value of the acceleration, $\int |a| dt$. Although named the “Cumulative Absolute Velocity,” the CAV is not directly related to the ground motion velocity (integral of acceleration), but it does have units of velocity (g-s).


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# Standardized CAV Determination

- An acceleration time history is first fully rectified, i.e., $\underline{a}_i(t) = |a_i(t)|$
- Then each 1 second interval of the time history is examined for the threshold value exceedance, $\underline{a}_i(t) > 0.025g$
- If the threshold value is exceeded at any time during that 1 second interval, then the area under the rectified time history is computed for that interval
- The sum of all such interval areas that have a threshold exceedance of 0.025g is defined as the CAV value, or

$$CAV(t) = \sum_i \int_{ti}^{ti+1} S_i \, |a| \, dt$$

where $S_i = 0$ for $|a| < 0.025g$ and $S_i = 1$ for $|a| \geq 0.025g$



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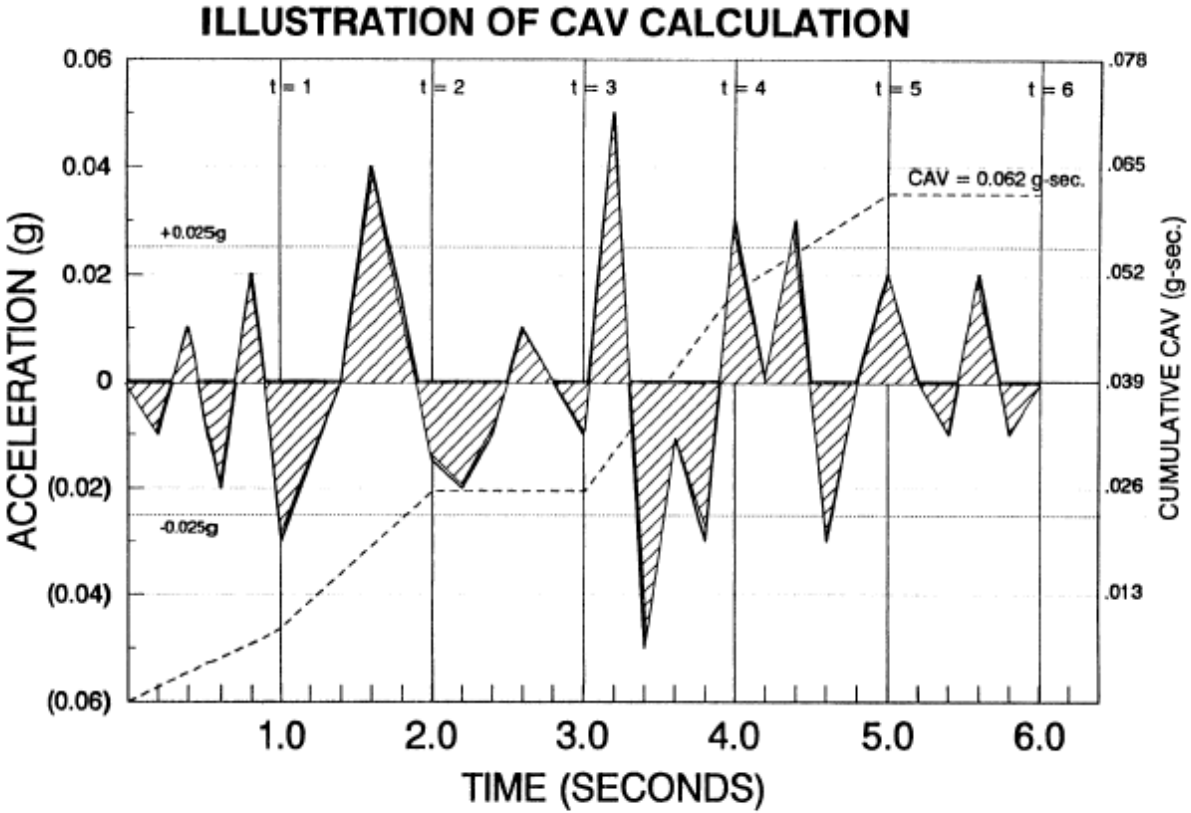


Figure 4-1. Illustration of the Standardized Method to Calculate CAV



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# Use of CAV

- TR-100082 studied 177 records and determined that the minimum standardized CAV value ($CAV_{STD}$) associated with a site intensity **MMI VII** (defined as the threshold of damage) was 0.16 g-sec.
- This value was incorporated into RG 1.66 as part of the criteria to determine if the OBE had been exceeded at any plant site experiencing an earthquake

(Brief introduction to the Modified Mercalli Intensity (MMI) Scale in the next slides)



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# Modified Mercalli Intensity (MMI) Scale

- MMI scale was developed in 1931 by the American seismologists Harry Wood and Frank Neumann

- The **MMI scale** describes the intensity of an earthquake based on its **observed effects**, while e.g. the **Richter scale** describes the earthquake magnitude by **measuring the seismic waves** generated by an earthquake.

- The MMI scale is a 12-grade scale (I-XII) currently used in the US.


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## Magnitude/Intensity Comparison

***Intensities typically observed at locations near the epicenter of earthquakes of different magnitude***

| Magnitude | Typical Maximum MMI |
|---|---|
| 1.0 – 3.0 | I |
| 3.0 – 3.9 | II – III |
| 4.0 – 4.9 | IV – V |
| 5.0 – 5.9 | VI – VII |
| 6.0 – 6.9 | VII – IX |
| 7.0 or higher | VIII or higher |

Buildings of **Good Design and Construction** is described as conventional building construction e.g. block and brick walls reinforced with steel not necessarily designed by an engineer . The EPRI Report NP-5930 considers this type of conventional building as a **conservative surrogate** for the seismic capacity of NPPs.

**$CAV_{STD}$** = 0.16g-sec corresponds to the minimum value for **MMI VII**

## Abbreviated Modified Mercalli Intensity Scale

| | |
|---|---|
| I | Not felt except by a very few under especially favorable conditions. |
| II | Felt only by a few persons at rest, especially on upper floors of buildings. |
| III | Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated. |
| IV | Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably. |
| V | Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop. |
| VI | Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight. |
| VII | Damage negligible in buildings of **Good Design and Construction**; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. |
| VIII | Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. |
| IX | Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. |
| X | Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent. |
| XI | Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly. |
| XII | Damage total. Lines of sight and level are distorted. Objects thrown into the air. |



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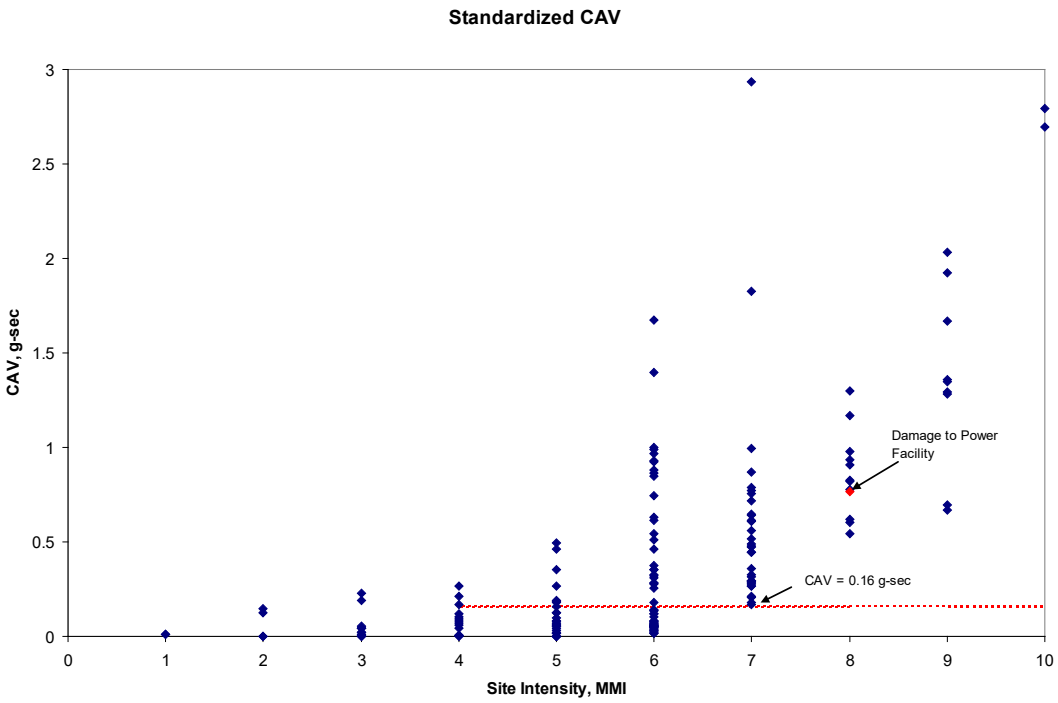
# TR-100082 Results

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# Important Points

- MMI intensity is determined by structural damage
- MMI VII is associated with damage to non-engineered structures, and therefore a CAV ≈ 0.16 g-sec was chosen as the conservative threshold of any type of damage to engineered structures
- MMI VIII is associated with minor damage to engineered structures – a CAV ≈ 0.8 g-sec is the threshold value for a SQUG database power plant having minor structural damage. Equipment at the plant, however, remained functional
- The use of a CAV damage threshold of 0.16 g-sec for a nuclear power plant is very conservative criteria


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# Damage Potential to RC Structures

- In a study[1] presented at the World Conference on Earthquake Engineering (WCEE) in Lisbon 2012 damage to Reinforced Concrete (RC) structures is correlated to $CAV_{STD}$

- The basis to correlate RC structure damage to $CAV_{STD}$ is the developed relationship between $CAV_{STD}$ and Japan Meteorological Agency Macroseismic Scale (JMA)/European Macroseismic Scale (EMS).

1) *K.W. Campbell and Y. Bozorgnia. Use of Cumulative Absolute Velocity (CAV) in Damage Assessment*
https://www.iitk.ac.in/nicee/wcee/article/WCEE2012_2965.pdf
*(Partially funded by IAEA as part of the Seismic Working Group 1)*


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# Damage Potential to RC Structures

- The JMA provides qualitative levels of damage to RC structures of **Low** or **High** earthquake resistance
- The EMS provides qualitative levels of damage to RC structures of three earthquake-resistant design (**ERD**) categories; **None**, **Moderate** or **High**
- The EMS states that
  - ***Moderate ERD*** structures typically are designed for a base shear of about 5-7 % g, and
  - ***High ERD*** *structures for a base shear of about 8-12 % g*


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# Summary study presented at the WCEE 2012

- ***CAV*** threshold values corresponds to onset of damage to RC structures. In the EMS described as cracks in columns and beams and in structural walls.

| Level of Earthquake-Resistant Design | | | CAV [g-sec] | | |
|---|---|---|---|---|---|
| ***MMI*** | ***EMS*** | ***JMA*** | $P_{ne} = 1\ \%$ | $P_{ne} = 5\ \%$ | ***Median*** |
| Good Design & Construction | None | Low | 0.19 | 0.26 | 0.54 |
| Specially Designed | Moderate | High | 0.32 | 0.43 | 0.88 |
| Specially Designed | High | High | 0.52 | 0.70 | 1.43 |

$P_{ne}$ refers to the non-exceedance probability, i.e. the probability that damage occurs below the CAV threshold.



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# Representative ERD for Swedish NPP RC Structures

- Oskarshamn 3/Forsmark 3 are designed in accordance with US NRC Regulatory guide 1.60 anchored to PGA 0.15g horizontal.
- In the frequency domain 5-10 Hz the horizontal spectral acceleration is about 0.5g
- Seismically designed buildings at O3/F3 may therefore be categorized as **High ERD**


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# Representative ERD for Swedish NPP RC Structures

- Forsmark 1 & 2/Ringhals 3 & 4 are originally not designed for seismic loads
- Structures needed for SSE have been demonstrated to withstand seismic loads applying modern building codes
- Seismic ground motions assumed in analysis in accordance with the Swedish GMRS (horizontal PGA 0.11g)
- In the frequency domain 5-10 Hz the horizontal spectral acceleration is in the range of about 0.17g to 0.35g
- Seismically verified buildings at F1/F2 and R3/R4 may therefore (at least) be categorized as ***Moderate ERD,*** since not originally designed for seismic loads.


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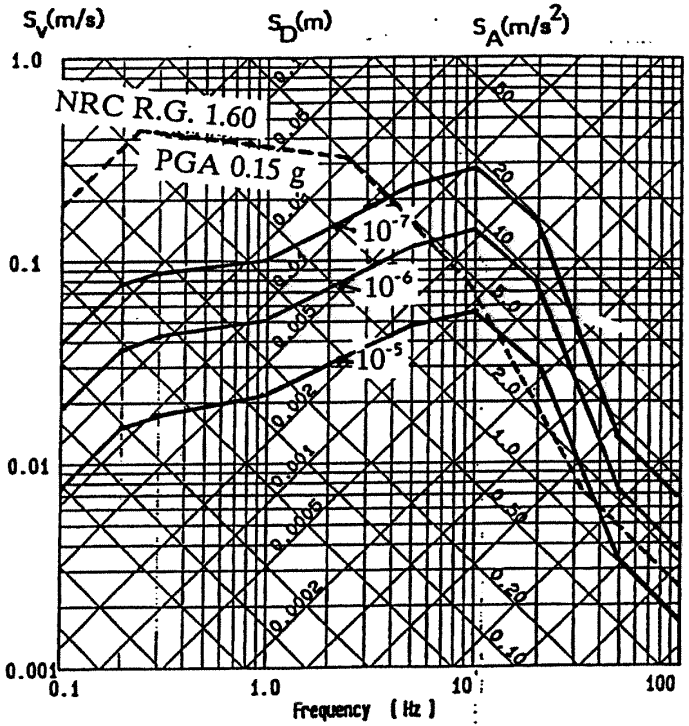
# Swedish hard rock ground response spectra




- Based on a regional seismic hazard study (SKI, 1992) uniform hazard ground response spectra for various exceedance frequencies were outlined.
- Applicable for a “typical hard rock site” in Sweden.
- Consideration of site effects leads to a reduction by 15% to account for the favorable site conditions as all plants are sited on solid rock.

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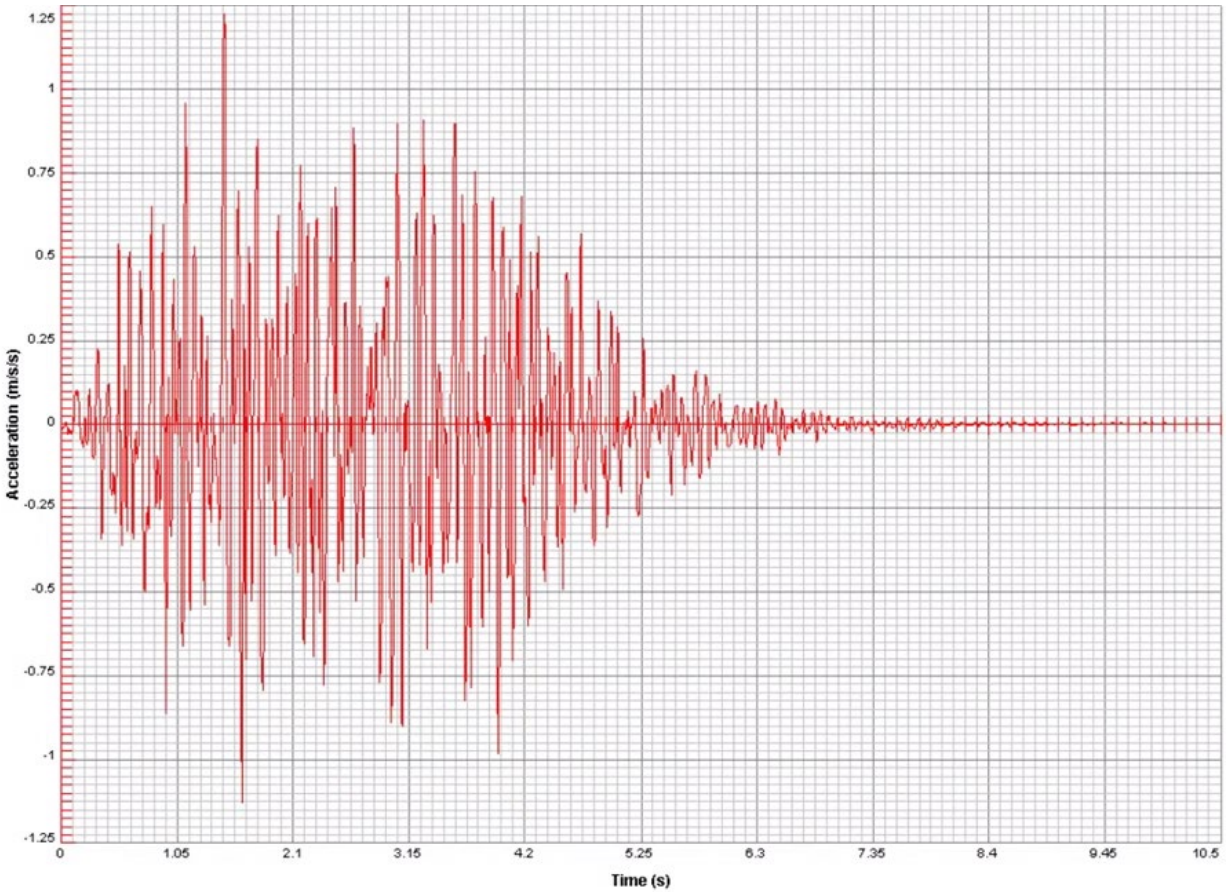
# Time-histories Swedish GMRS

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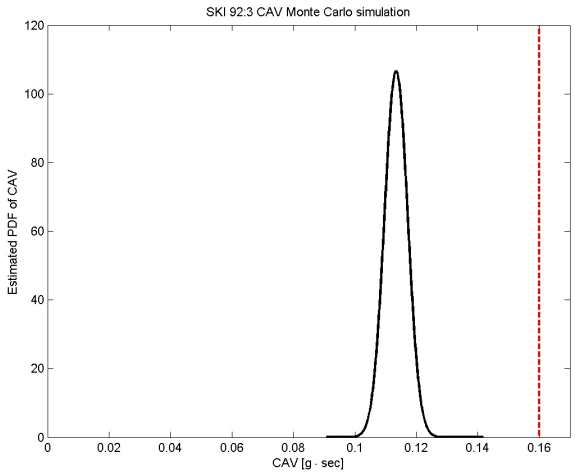
# CAV BASED ON SKI 92:3 E-5 ENVELOPE SPECTRUM




- CAV computed for artificial TH for Swedish earthquake.
- A conservative CAV-estimate for the E-5 spectrum is 0.13 gsec
- A seismic event of magnitude equal to Swedish DBE loading will not require any plant shutdown if such an event occurs at a US site.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# Damage Potential to Swedish NPP RC Structures - Summary

**Comparison of**

1. the $CAV_{STD}$ thresholds for damage onset to RC structures, with
2. the $CAV_{STD}$ value of 0.13 g-sec for the Swedish GMRS, implies that

- The damage potential to NPP RC structures is negligible from a global structural perspective
- Seismically classified RC structures exhibit large margin to $CAV_{STD}$ thresholds for damage onset

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# Historical Swedish Perspective

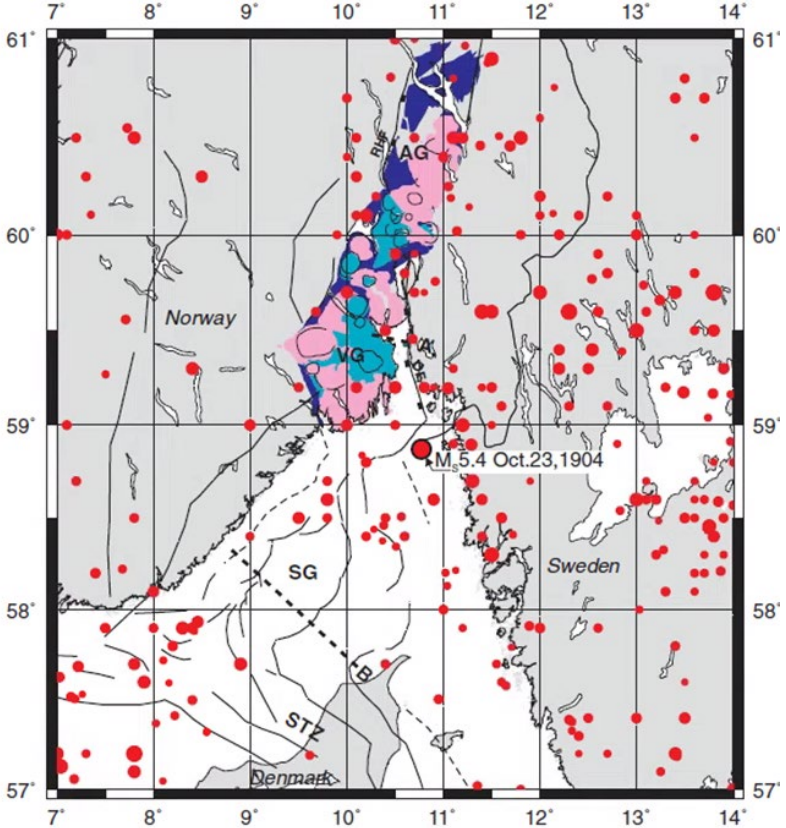
The largest earthquake (estimated to M=5.4) in Sweden's vicinity in (reasonable) historical time occurred 23 October 1904 offshore in the Oslofjord with the Swedish Koster islands nearest the epicenter

Intensity up to MMI VII

The earthquake was felt over large parts of Norway, Sweden, and Denmark

Modest damages were limited to wooden and un-reinforced masonry buildings close to the epicenter

The old stone church in Idd from about year 1100 (near Halden) had more severe damages, but was later restored and used for services again in year 1922





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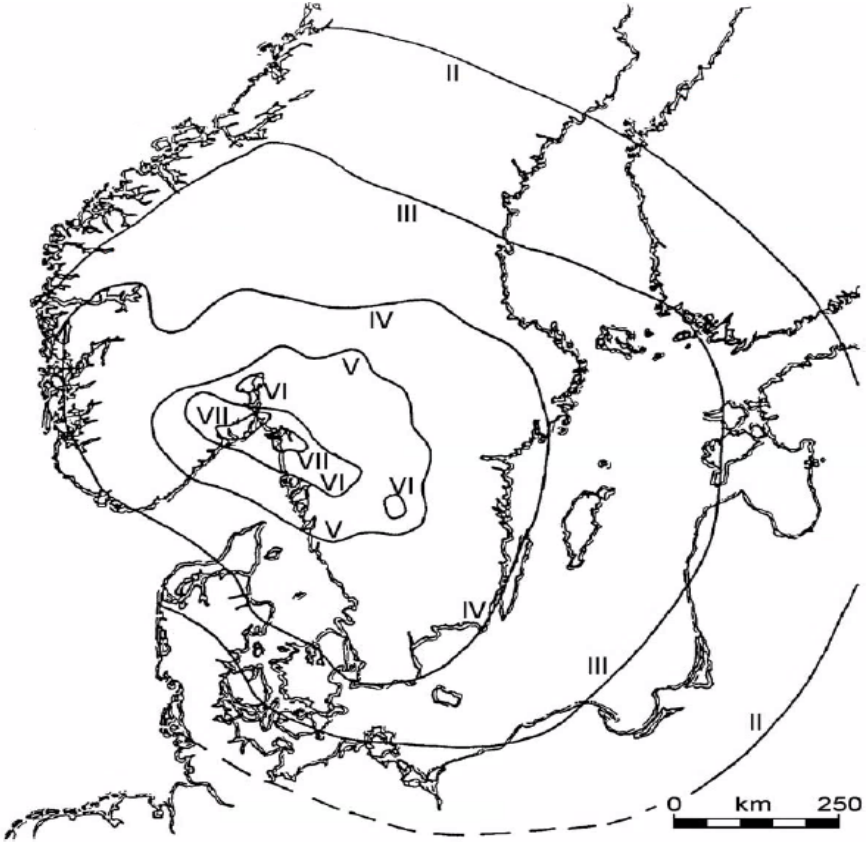
# MMI Isoseismals for the Oslofjord Earthquake 1904

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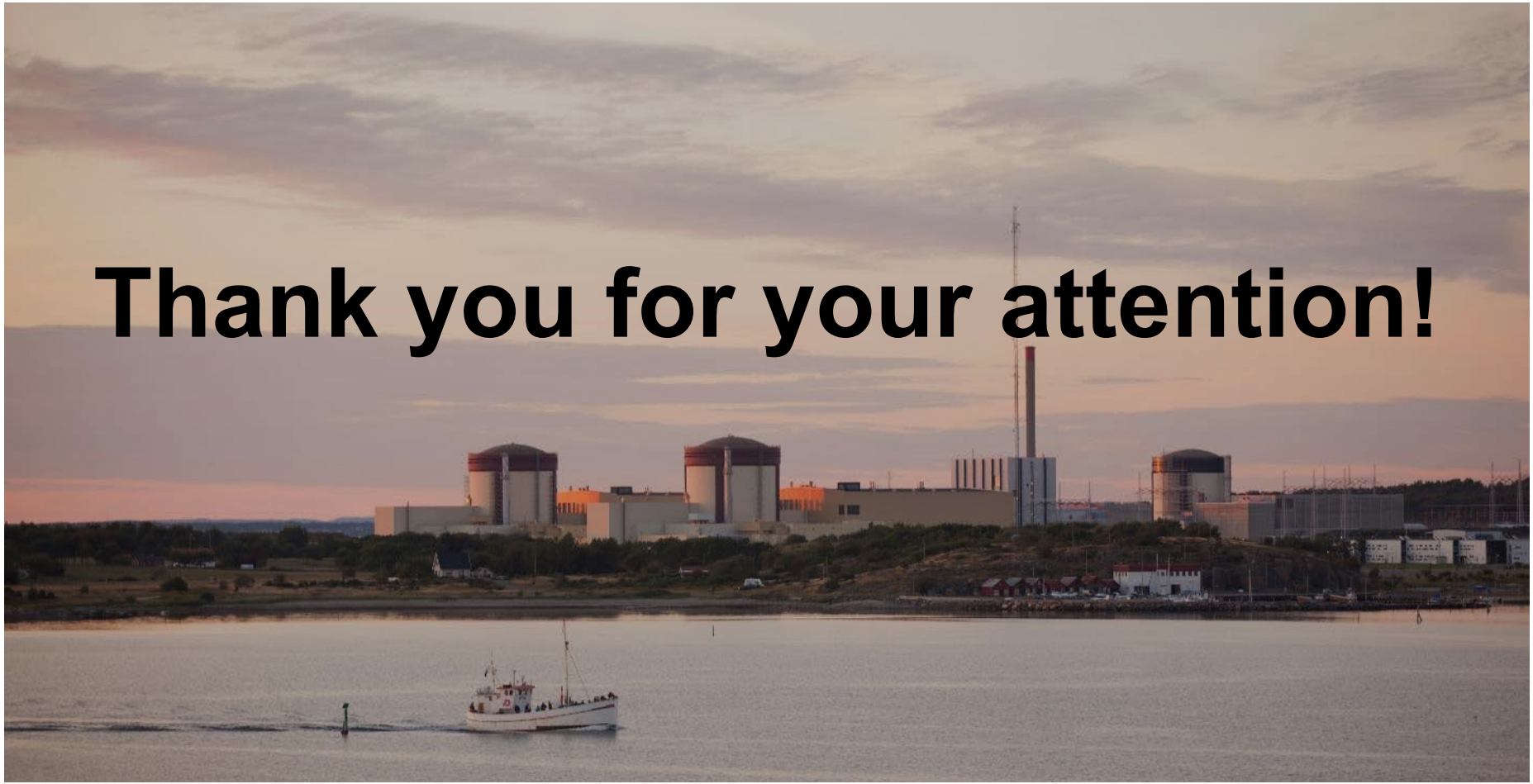
Thank you for your attention!