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Resilience of nuclear power plants to seismic risk: case study of the Le Teil earthquake

This report is the outcome of a work seminar held in March 2020 by SFEN Technical Sections no. 04 (nuclear safety and environmental protection) and 09 (civil structures and nuclear architecture). SFEN would like to thank the guest subject-matter experts for the high standard of discussion and diversity of experience and viewpoints, as well as for the depth and openness of dialogue.
We would particularly like to thank D. Grenié and A. Vallage (CEA), E. Viallet (EDF), C. Clément (IRSN) and B. de l'Epinois (SFEN ST4 chairman) for the preparation and review of this position paper.

Summary

We considered this investigation to be all the more necessary given that – in terms of communication and the sharing of knowledge, which is the SFEN's fundamental purpose – we experienced a certain number of issues: discussions focusing on nuclear power plants which did not suffer any damage, rather than on the severely damaged villages; a plant that remained shut down for almost one month in spite of having suffered no adverse effects whatsoever; the use of different terms to describe the earthquake (magnitude) or its potential effects on plant facilities (acceleration, "response spectrum"); last but not least, three types of magnitude used by technicians, of which the values have evolved along with the precision of calculations[1].

This report describes our understanding of the seismic event (facts that we are certain of today and other items that still need to be explored further), reviews the safety measures taken on French nuclear facilities to control seismic risk and summarises the procedures used in response to this event and the effects observed on nuclear facilities in the region.

It highlights the following:

- From a seismological standpoint, the Le Teil earthquake is not a novel occurrence in the Rhone Valley. Nor is it a surprise, given that it is of the same nature and of a similar scale as earthquakes regularly observed throughout the history of the Rhone Valley. Its most unusual feature, not unknown in the region, relates to the shallowness of its seismic source.

- The key parameters of this earthquake (location, fault slip, magnitude, depth) were established in the days, weeks and months that followed it. The results were gradually fine-tuned and the various methods converged. Large amounts of data still need to be processed, making it possible to specify and validate the seismological models and techniques.

[1] Estimates are converging towards the following ranges: local magnitude of 5.1 to 5.4, moment magnitude of 4.8 to 5, surface-wave magnitude of 4 to 4.5. This level of magnitude is typical in a region of moderate seismicity such as South-Eastern France. Earthquakes in the most seismic regions such as along the Pacific faults can reach magnitudes of up to 8 or 9 (i.e. energy levels of nearly 30 000 to 800 000 times higher).

- On nuclear sites in the South-East (Cruas, Tricastin, Marcoule and Cadarache), the Le Teil earthquake only generated minimal accelerations, far below those considered in their design basis, and had no adverse effects on plant components.
  The latter was expected insofar as the seismic level recorded on these sites was far below the design-basis level: the Le Teil earthquake was of a similar scale to that which, by adding in a margin, forms the basis of Cruas' reference standards (the closest plant, about fifteen km from the epicentre); the quake was attenuated by distance; wide margins were built in at different stages of nuclear plant design.

- From a nuclear-safety perspective, operating experience firstly concerns investigation procedures used in the event of an earthquake, these procedures needing to be finetuned and made more direct and ready for immediate use. As is always the case in similar circumstances, design specifications for facilities located in the geological area of this earthquake will be reviewed in detail. This will include an examination of faults around the sites, the potential for surface ruptures, near-field movement characterisation and harmfulness, etc.

Introduction

The earthquake that occurred at Le Teil on 11 November 2019 was met with great emotion and surprise. The emotion was well-founded in view of the destroyed homes, cracked walls, homeless residents and their distress. The surprise was understandable: such phenomena are quite rare in a person's lifetime and by force of habit, we tend to forget about such eventualities.

However, it is actually not a surprise or rather, should not be a surprise for those who are involved with or interested in risk management. The earthquake is of a similar scale to other events having regularly occurred in the history of this region. These include, for example, the earthquake of 8 August 1873, which was used as a data point for the design of the Cruas and Tricastin reactors. This "similar scale" obviously needs to be specified and scientists are closely examining what new things we can learn from this specific event and whether certain parameters should be adjusted for purposes of seismic risk management. Nevertheless, it is not surprising that something similar to what happened in 1873 should reoccur, nor that it should not occur in exactly the same way. What is essential is the way in which plausible events remain within the design envelope and design margins of nuclear facilities.

Communication surrounding the Le Teil earthquake was beset by a number of paradoxes and difficulties: destroyed houses and intact nuclear facilities; discussions which quickly focused on nuclear power plants where no damage had occurred, rather than on severely damaged villages; a power plant that remained shut down for nearly a month although it had suffered no damage whatsoever, naturally leading the surrounding population to believe that something serious must have happened; different physical parameters depending on whether they were qualifying the earthquake (magnitude) or its potential effects on nuclear facilities (acceleration, response spectrum). To complicate things further, three types of magnitude were used by the technicians and evaluated using a variety of techniques, with results evolving as calculations became more precise.

Benefitting from a few months of hindsight, this report summarises what occurred inside the earth's crust from a geological perspective; it sets out what we know with certainty today and what will continue to be explored; it describes what was felt on nuclear sites in the region; how facilities are seismically designed and why it is normal that such an event did not affect them; how this type of event contributes to nuclear-safety enhancement efforts, which are a living endeavour.

1. The earthquake of 11 November 2019

a. Seismological description

The Le Teil earthquake occurred at 11.52 on the 11th of November 2019. The alert was raised by the CEA and the BCSF[2] issued the first press release at 12.16. At that time, the earthquake was semi-automatically estimated to be located to the south of Montélimar with a local magnitude of 5.4 (Figure 1). In the next 12 to 24 hours, a number of organisations published their "computations" based on records from seismological stations belonging to various observation networks in France or abroad. At the time, the epicentres were all scattered within a 10-km radius around the town of Le Teil and the depth of the earthquake's focus ranged from 3 to 12 km. Signal analyses then gradually became more precise.

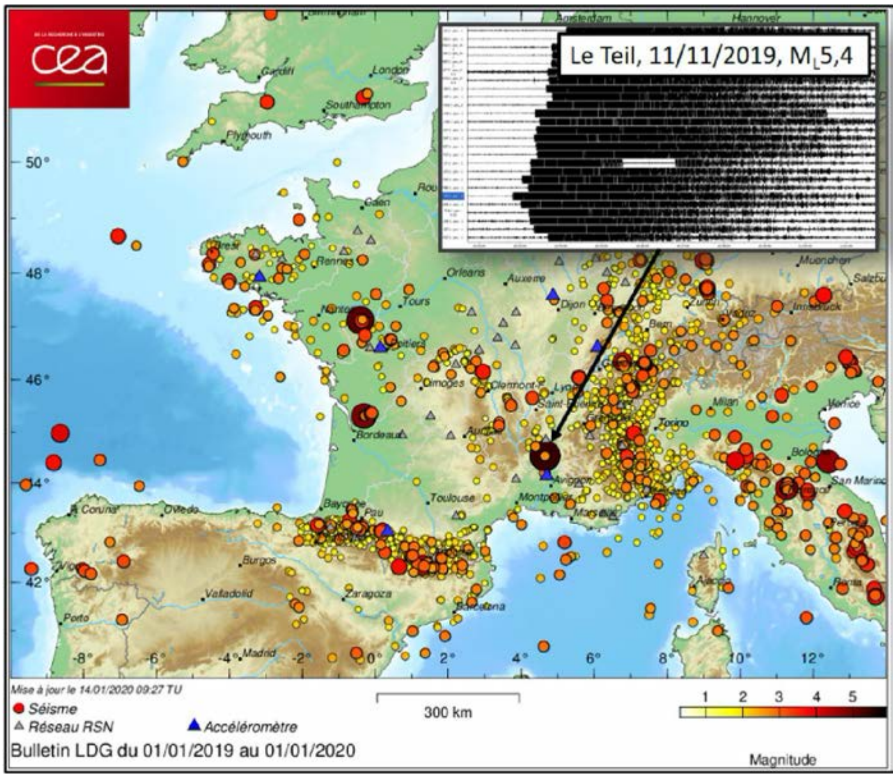

Figure 1. The Le Teil earthquake was the biggest to occur in 2019. The markings indicate the signals received in real time at 26 of the stations forming part of the national seismic network run by the CEA. They were used in the first attempt to automatically determine the earthquake's location in the minutes following the event. As per normal procedure, the event's characterisation was revised and approved in the first few hours following the earthquake by on-call seismological experts.

In the following days, an analysis of satellite observations using radar interferometry to compare the signals recorded before and after the earthquake (Figure 2) was performed in order to measure ground deformation with a very high degree of precision (a few cm). This data was used to help identify the source location of the earthquake (*Figure 3*): "La Rouvière" fault. Located to the south of the town of Le Teil, it faces NE-SW and the portion that ruptured during the earthquake is about 5 km long. Radar interferometry (InSAR) was also used in order to estimate maximum displacement along this fault (approx. 10 to 15 cm of displacement at the surface). The analysis also revealed the shallowness of the rupture (0 to 1.5 km deep) and confirmed the type of fault movement: overlap mechanism whereby the eastern compartment lifted by approx. 10 cm compared with the western compartment.

[2] France's Central Bureau of Seismology

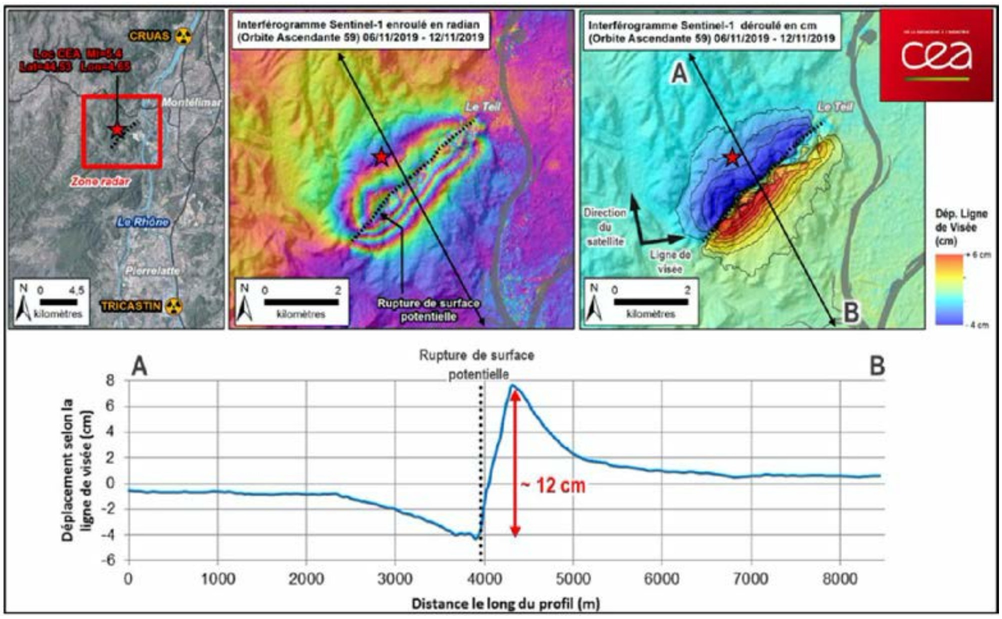

Figure 2. Initial results after satellite data was processed by the CEA during the days following the earthquake. The event's properties (location, depth, magnitude, focal mechanism, connection with the Rouvières fault, etc.) have since been specified.

Geologists from the universities of Grenoble, Montpellier, Nice and the Institute for radiation protection and nuclear safety (IRSN) went to inspect the location two days after the earthquake in order to observe signs of surface rupture produced by the fault. They performed discontinuity mapping of cracks and fractures with displacements of around one centimetre to ten centimetres.

The number of aftershocks following the quake was markedly lower than what is normally observed with an earthquake of this magnitude.

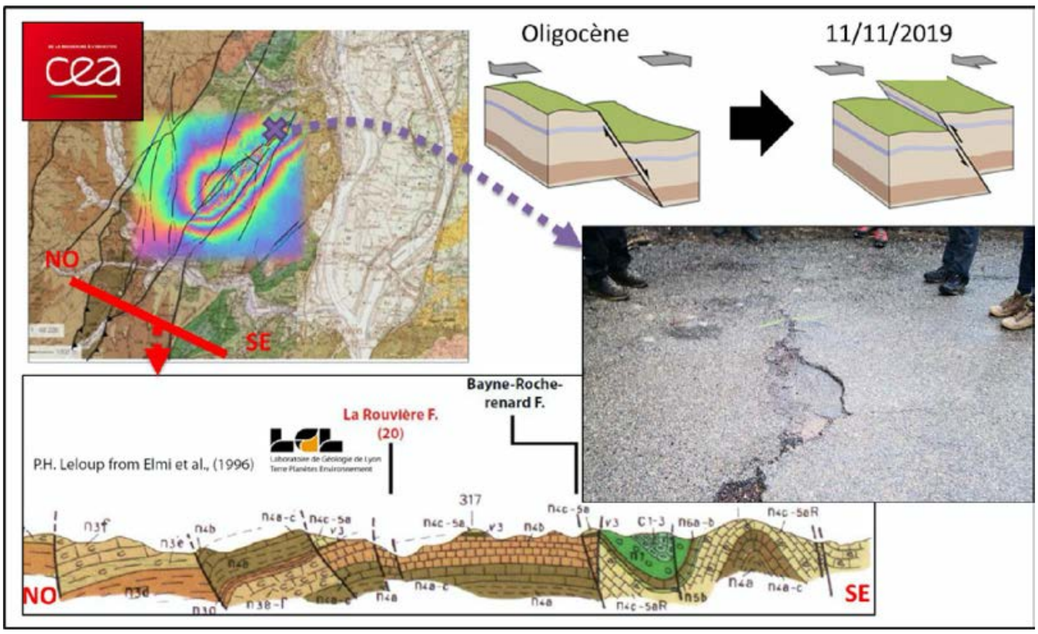

Figure 3. After comparing data gathered by different specialities (geology, field, satellite measurements, etc.), a link was very quickly established between the earthquake and the Rouvière fault: an old, normal fault affecting Oligocene deposits having generated reverse faults during the earthquake of 11 November 2019.

b. Surface effects

The earthquake was widely felt in south-eastern France, as far away as in Saint-Etienne, Grenoble, Lyon, Montpellier and Marseille. It was felt as a sudden quake, followed by an oscillation of 5 to 10 seconds, accompanied by very loud noises. Hundreds of buildings were damaged in the area, requiring hundreds of people to be evacuated.

Volunteers from the AFPS[3] carried out in-field examinations of the affected buildings. A mission from the Macro-seismic Response Group (Groupe d'Intervention Macrosismique: GIM) led by BCSF-RéNASS and involving the IRSN also inspected the location the week after the earthquake in order to assess the intensity of seismic movement by observing its effects. Twenty-four towns were inspected.

The radius including intensities of VI (occurrence of damage) covers about fifteen km, very similar to the same range observed during the earthquake of 8 August 1873. The intensity of the quakes in the epicentral zone reached VII degrees (in Viviers and Le Teil) and locally, VIII (Le Teil), i.e. 1/2 to 1 degree higher than current evaluations of maximum intensity during the earthquake of 1873.

With regard to ground movement, the first seismological stations run by France's observation networks[4], located approximately twenty kilometres from the epicentre, recorded accelerations of a few thousandths of a g (g being gravity acceleration), e.g. 6 mg (0.006 g) close to Tricastin nuclear power plant. At Cruas, about 15 km away, sensors recorded a maximum acceleration of 45 mg (0.045 g) in free field (see below). (*Figure 4*)

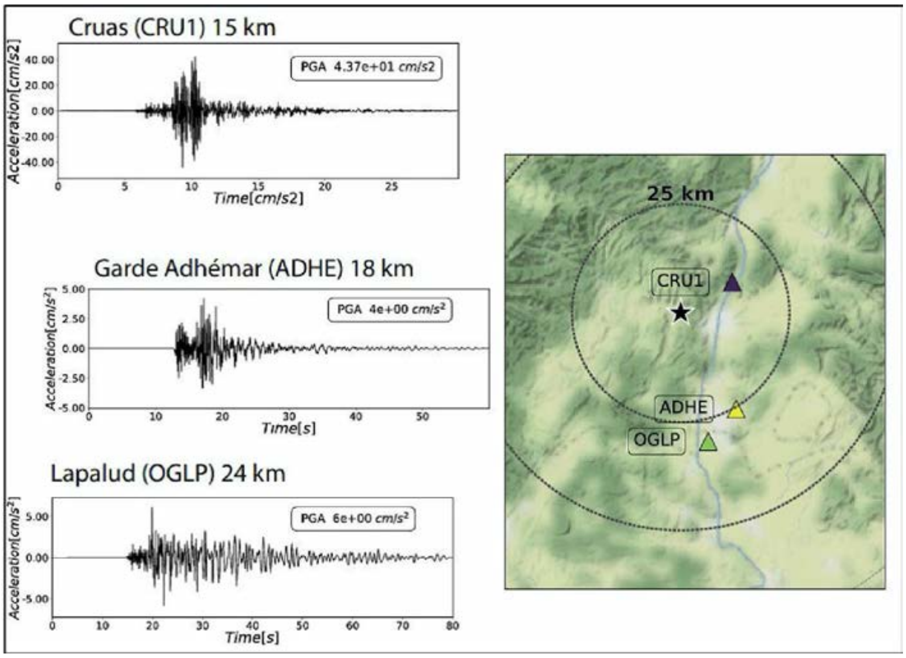

Figure 4. Ground accelerations (1 cm/s^2 = 1 mg) recorded at seismological stations run by EDF (Cruas) and Résif (France's seismological and geodesic network) which were located within a 25-km perimeter around the Le Teil earthquake.

It is worth noting that other seismological stations used for industrial or research purposes also recorded the earthquake. These records will be used to fine-tune the analysis of the earthquake's location, of rupture propagation direction and of ground movements.

[3] French Association of Seismic Engineering

[4] Résif: *France's seismological and geodesic network*

c. Regional seismotectonic characteristics

The earthquake of 11 November 2019 occurred in a region characterised by moderate but relatively frequent seismic activity. There is historical evidence of this activity, going back to the 16th century and even earlier. As an example, the archives contain witness accounts of an earthquake that occurred at Châteauneuf-du-Rhône on 19 July 1873.

A report from the town of Viviers: "At 03.40 this morning, a violent earthquake occurred which made the one that happened on the 14th of the month seem like an insignificant precursor. It startled the peaceful inhabitants of Viviers. The quake was so violent that the town's entire population fled their shaken houses in panic. We saw cracked walls, collapsed chimneys, tables and beds that had changed position. Bells were jangling, terrified animals were screaming and howling pitifully; the noise was like underground thunder, it sounded like violent tearing and whistling. People who were outdoors at that early hour of the morning witnessed the movement that the quakes imprinted in the earth and told us that they looked like waves. The trees were shaking violently as if they were being uprooted by an invisible hand". (J. Annonay).

On 8 August of the same year (1873), a very similar earthquake occurred in the same region. Researched in greater detail, this earthquake was used as a reference for Cruas and Tricastin. A number of these occurrences are reminiscent of the witness accounts gathered after the earthquake of 11 November 2019, which affected the same town.

These witness accounts were used to characterise previous earthquakes. Set up by BRGM, EDF and CEA more than 30 years ago, the SisFrance database, now being developed by BRGM, EDF and IRSN, contains an inventory of all known historical earthquakes. The observations kept in the archives are recorded in terms of intensity (an assessment of the earthquake's surface effects).
To the north and east of the Plaine du Tricastin, seismicity is generally characterised by quakes accompanied by dull noises similar to explosions or thunder claps. They may reoccur for several weeks or months and are characterised by "swarms" of seismicity. This applies to the earthquakes of 1773, 1873, 1933-1936 and 2002-2003. The most significant effects were observed in 1773, 1873 and 1934, associated – according to the SisFrance database – with an epicentral intensity of VII (pronounced damage to numerous dwellings). The "swarm" of 2002-2003 showed very shallow seismicity (depth of approx. 1 km max.).

The Rouvière fault on which the earthquake occurred is shown on geological maps but was not known to be active in the recent period. It forms part of the large Cévennes fault system which extends over more than 100 km between the Massif Central and the Western Alps, and which has had a long geological history for more than 200 million years. It was generated by extension stresses during the Mesozoic and Oligocene epochs (20 to 30 million years) and is now generated by compressive stresses. Other potentially active faults have been identified less than 10 km away. This highlights the value of studying faults even in moderately seismic conditions.

d. Different types of magnitude

An earthquake can be characterised by its magnitude and depth. Magnitude represents the earthquake's energy. There are a number of magnitude scales that have been developed along with the progress made in the area of seismology:

- Local magnitude (ML) is evaluated on the basis of the signal's maximum amplitude;
- Moment magnitude (MW) is estimated on the basis of full signal inversion; it is also evaluated using rupture dimensions of the fault having caused the earthquake when they can be estimated using other methods (e.g. Insar);
- Surface-wave magnitude (MS) is evaluated using the component of the signal characterising the surface waves.

These three methods generally result in different values. Seismic monitoring networks use local magnitudes (ML – calibrated differently for each network). In the field of seismology, moment magnitude (MW) is often used. In France, the scale used for nuclear facilities is surface-wave magnitude (Ms).

As far as historical earthquakes are concerned (for which there are no records and for which only the observed macro-seismic intensities are available), surface-wave magnitude is calculated by correlating magnitudes and intensities, established on the basis of recent earthquakes where both magnitude (deduced from records) and intensity are observed.

e. Magnitude and depth of the Le Teil earthquake

The different evaluations of local magnitude resulted in values ranging from 5.1 and 5.4. Moment magnitude ranges from 4.8 to 5.
Surface-wave magnitude estimations range from 4 to 4.5:

- The IRSN asked the ISC (International Seismological Centre) to compute this magnitude based on the signals of seismological stations located around the world: a value of approx. 4.4 (+/- 0,2) was obtained;

- The last value established by the CEA's Geophysical Detection Laboratory, based on signals from 48 stations around the world, is 4.2+/-0.3 (see event report on the CEA website[5]).

Satellite radar interferometry analyses converge towards a maximum fault slip at 1 km in depth. Seismological data is still being analysed.

f. Items needing further clarification

From a scientific standpoint, a lot of data remains to be analysed: hypo-central location, recorded movements compared with those deduced from prediction models, acceleration in the epicentral zone, property of rocks on the fault plane and in the fault's environment, source characteristics, geometry and activity of faults in the Cévennes fault bundle, connection with Tricastin swarms, etc.

For this purpose, seismologists use a variety of highly sophisticated technologies such as satellite radar interferometry (InSAR, see above), a wide range of signal processing methods based on records from seismological stations, and seismic-wave propagation modelling, etc. Signal inversion techniques are used, for instance, to estimate the direction of the fault, its dip and the surface involved during the event, etc. Radar interferometry is also used to estimate slip spatial distribution through cross-correlation between the deformation observed at the surface and modelling results for different fault slips and different rupture depths.

Seismologists from Nice, Grenoble and the IRSN coordinated their actions in order to quickly set up seismological stations in the epicentral zone and to record aftershocks as near as possible to the focus, as well as to closely analyse the fault plane and the attenuation of waves in the area.

g. The site effect

In a given location, when seismic wave propagation speed is less than the wave speed deeper in the ground, the seismic signal is amplified and lengthened. To a certain extent, the ground acts like an amplifier and waves can become "trapped" in lower-velocity areas. This is particularly the case when the ground comprises thick layers of unconsolidated sediment of which the propagation speed is slower, above harder rocks of which the propagation speed is higher.

[5] http://www-dase.cea.fr/actu/dossiers scientifiques/2019-11-11/index.html

As an example, after the level of the Mediterranean dropped about 6 million years ago, the Rhone River carved deep geological formations, creating a canyon. The latter was then filled with softer sediment (sand and clay) than the surrounding rock.

We are well aware of these phenomena. In fact, the Basic Safety Rule (RFS2001-01 see below) requires potential site effects to be considered when propagation speed underneath the site is in a low range and in the event of significant thickness or complex geometry of the sediment layers. Since this Rule was issued, research has continued in order to be able to model site effects in 2D and 3D. This involves the use of highly sophisticated techniques in the field of geophysical characterisation and mathematical modelling of sedimentary basins (Figure 5).

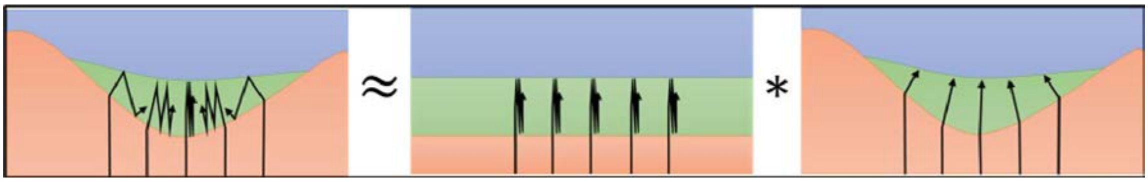

Figure 5. At first glance, the "geometrical" site effect (on the left) can be seen as the combined result of two phenomena: the "1D" effect (in the middle) and the "2D/3D" (on the right).

In the Rhone Valley, Cruas nuclear plant – located on the edge of the "canyon" – is built on rock: it is not subjected to site effects. Tricastin, built on sediment, is subjected to site effects. Following the Le Teil earthquake, the IRSN compared the signals recorded by different sensors placed near Tricastin, some on the rock at the edge of the canyon and others on the sediment. The signals confirmed the existence of a site effect: amplification and lengthening of the signal[6]. A site effect is actually considered in determining the postulated spectrum. Recent EDF modelling work has concluded that there are no additional significant 2D/3D effects perpendicular to the Tricastin site. These are undergoing further analysis and R&D work is continuing on this subject.

h. What about the quarry?

At this stage, the theory according to which an interaction may have occurred between the seismic rupture and a quarry located just above the fault must be considered. However, if the quarry did influence the triggering and propagation of the rupture (which is only an assumption to date), this will remain difficult to prove. Whatever the case may be, the stresses having built up on the fault are essentially due to tectonic forces. The fault was bound to break sooner or later, depending on the geological time scale. This data will inform R&D work.

[6] https://www.irsn.fr/FR/Actualites presse/Actualites/Pages/20191126 NI-Seisme-du-Teil-11112019.aspx

2. Review of nuclear-safety measures

a. From magnitude to acceleration

The main seismic design parameter used for plant facilities is acceleration. Acceleration is what determines the seismic forces that structures and components must be able to withstand (ΣForces = m.Y). For this reason, seismic load is mostly expressed in terms of acceleration or more precisely, by its oscillator response spectrum, in order to determine a structure's or component's maximum response to seismic load. This method is applied to the ground (ground-response spectrum) or inside buildings (floor-response spectrum)[7]. The 900-MWe plant series (including Cruas and Tricastin) was designed on the basis of a 0.2g ground-response spectrum. This seismic level is known as a design-basis earthquake (DBE) and must obviously be more less or equal to the site's seismic hazard level.

b. RFS (revision 2001)

The basic safety rule used for defining seismic hazard is deterministic.

1 / It firstly requires the delimitation of seismotectonic boundaries within which the potential for earthquakes is homogeneous (probability and characteristic of earthquakes). (Figure 6)

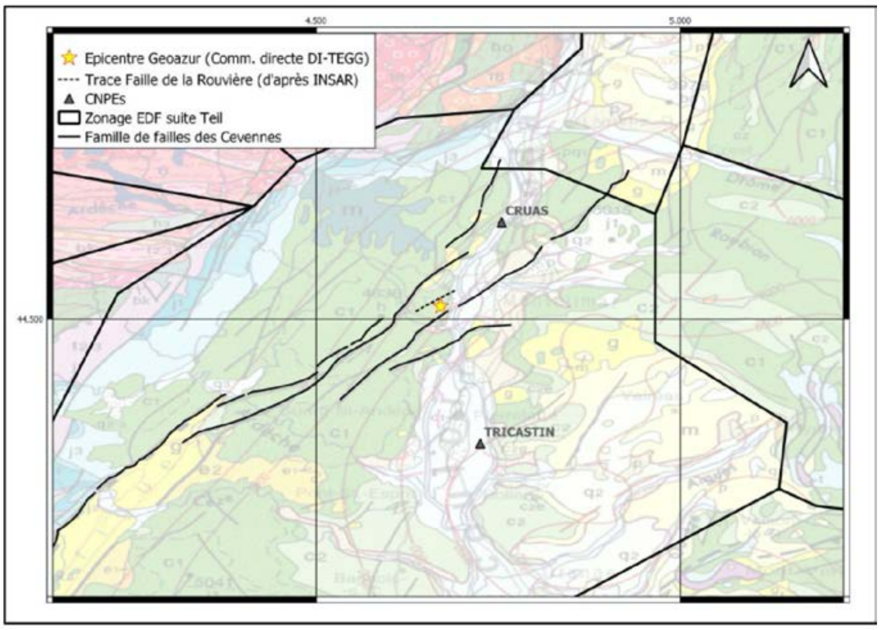

Figure 6. Example of seismic zoning around the Cruas and Tricastin sites, showing the group of Cévennes faults.

2/ The most powerful (historical) earthquakes in each zone (in macro-seismic intensity) are then selected and conservatively translocated within their zone closest to the site (perpendicular to the site if they are located in the same seismotectonic zone as the site, or translocated along a fault system when attached to it). This determines the maximum historically probable earthquake(s) (MHPE).

3/ The postulated MHPEs' magnitude and depth then have to be calculated.

4/ Intensity and magnitude are increased by one degree in intensity (MSK scale) and by one-half a degree in magnitude (surface) (both these operations being equivalent), in order to establish the safe shut-down earthquake (SSE), which forms the design basis for the construction of nuclear facilities.

5/ In addition to historical earthquakes, the RFS also requires an analysis of paleo-earthquakes (earthquakes preceding the historical period, of which geological remnants can be found in order to determine characteristics such as magnitude or return period).

[7] In some cases, seismic movement modelling has to be supplemented by other parameters such as speed, displacement and time series (time histories) which can better characterise the damage potential of seismic movement.

6/ Lastly, the SSE's seismic characteristics are converted into ground movements (acceleration, amplitude, frequency, oscillator response spectrum). It is the ground's movement that affects plant facilities: it serves as the working basis for engineers when designing and demonstrating the resilience of structures.
7/ The RFS also requires any site effects to be considered (see above).

The design of nuclear facilities therefore includes three safety-margin levels with regard to seismic risk: translocation of the MPHE as close to the site as plausible; increasing the MPHE to establish the SSE; significant margins in structure design. The latter are the result of conservative codes and criteria; they have been confirmed by experience on the occasion of real earthquakes (e.g. Kashiwazaki-Kariwa, Onagawa, North Anna, Perry) and by laboratory tests.

Seismic risk and the ability of power plants to withstand them are reviewed on the occasion of each ten-yearly periodic safety review, and when called for by specific events.

c. Supplementary safety assessments

For the purpose of supplemental safety reviews conducted further to the Fukushima accident, licensees verified the robustness of their facilities in the event of an earthquake significantly greater than an SSE, referred to as "hardened safety core (HSC) earthquakes". New hardened-core components have been designed on the basis of this seismic level from the outset. The HSC spectrum is defined as the SSE bounding spectrum of which accelerations are increased by 50% and of which the return period is at least 20 000 years.
In addition to a deterministic approach, a probabilistic approach was used in order to determine the applicable seismic levels, beyond design, for hardened safety cores.

d. Approach applied to the design of French nuclear power plants

The design of France's Pressurised Water Reactors (PWR) is based on a "series" principle: building superstructures (above the base-mat) and systems and components of the nuclear island are identical for all sites of the same reactor series[9]. This standardisation is based on bounding assumptions seeking to cover ground conditions and the seismic levels of the sites in question.

e. Specific case of Cruas NPP

During the design phase of the 900-MWe reactor series (in the mid-70s), Cruas site hazard studies culminated in the determination of an earthquake acceleration value that was set at 0.3g. This seismic level, significantly higher than that of the reactor series' DBE (0.2g), combined with particularly stiff soil conditions, prompted EDF to build the plant on earthquake-resistant bearing pads[10] in order to keep civil structures, systems and components of the nuclear island identical to those of the rest of the reactor series (Figure 7, Figure 8). This technology "filters" seismic movement by considerably reducing accelerations felt by structures and components.

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[8] Translocating the reference earthquake of the seismotectonic zone underneath the site provides a significant margin from a probabilistic viewpoint. For example, let us assume that the seismotectonic zone is a 40 x 40 square (1600 km^2), that the likelihood of an earthquake is homogeneous throughout the area, that a MHPE-type earthquake occurs there once a century (what has been observed in the Rhone Valley to date) and that the epicentral zone covers a surface area of 10 km^2 (a radius of approx. 2 km). In probabilistic terms, this reference earthquake occurring in the area every 100 years would be located under the site, like in any point of the area, every 16 000 years. If the zone was a 100x100 km square (10 000 km^2), the return period would be 100 000 years.

[9] The EDF reactor fleet comprises four reactor series: 900 MWe, 1300 MWe, 1450 MWe (N4) and EPR (1650 MWe)

[10] The technology of Cruas' earthquake-resistant bearing pads is that of Spie-Batignolles and Freyssinet (reinforced elastomeric bearing pads) for which substantial operating experience was available, including use on a number of art works.

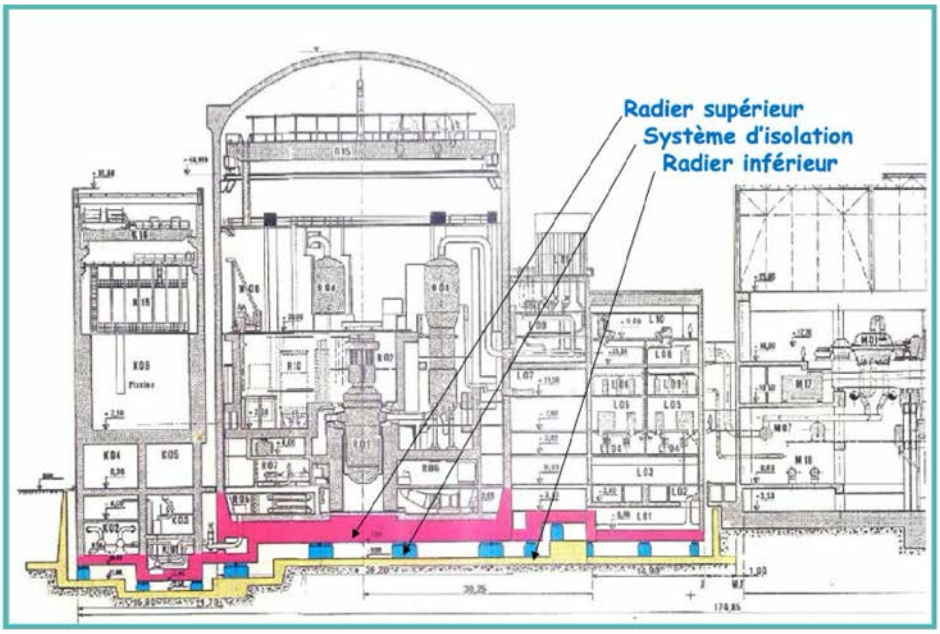

Figure 7. Section of a nuclear island at Cruas NPP, showing the earthquake-resistant isolation system as well as the lower and upper base-mats.

Figure 8. Photos of earthquake-resistant bearing pads and their reinforced-concrete support blocks.

3. Effects on nuclear facilities in the region

a. Cadarache, Marcoule, Tricastin

As far as the CEA sites of Cadarache and Marcoule are concerned and given their distance from Le Teil, the earthquake had no effect on these facilities. Marcoule, the closest site located approx. 45 km away, only recorded an acceleration spike of a few mg. With regard to a potential seismic hazard revision for these sites, as the earthquake is linked to the Rouvière fault forming part of the Cévennes fault group, the minimum distance of earthquakes within this fault bundle is high whatever the case, compared with CEA centres. Even by translocating the event right along the Cévennes fault bundle, the associated maximum acceleration spectrum would remain far below the thresholds hitherto considered for these sites. A seismic hazard revision on these sites has therefore been ruled out by the CEA for the present time. Nevertheless, this event will obviously be considered in future seismic hazard revisions and current research work is being conducted with this in mind.

As for Tricastin NPP (EDF), the perceived accelerations have remained below the threshold of 0.01 g: the reactors have continued to operate without any specific instructions. For the same reasons as those explained above, EDF has ruled out a seismic hazard revision for this site at the present time. These positions will be reviewed by the IRSN and ASN (France’s nuclear regulatory authority).

b. EDF operating procedures in the event of an earthquake

In addition to the facility’s seismic design, operating procedures guide the licensee when it comes to dealing with a seismic event, whether or not it is higher than a DBE.

The main control room is equipped with permanently installed seismic instrumentation that warns control-room operators (via an alarm) as soon as a quake exceeds 0.01 g (i.e. 5% of a DBE for the 900 MWe reactor series). When this threshold is exceeded, the quake is recorded at various points on the plant[11] and a specific operating procedure is applied (ref. EAU).

Additionally, an inspection earthquake has been determined. Its trigger point has been set at 0.05g (horizontal ground acceleration) for the entire French fleet. An additional value depending on the vertical component is included in the current procedure (equal to 2/3 of 0.05g, i.e. 0.033g)[12].
If the inspection earthquake threshold is exceeded, the licensee is required to shut down the reactors and undertake further investigations to ascertain the sound condition of the facility prior to restart.

c. Events occurring at Cruas

At Cruas, as the acceleration was higher than the 0.01 g threshold, operators immediately applied the EAU procedure, enabling them to rapidly evaluate plant condition and analyse data from the seismic instrumentation.

In the afternoon of 11 November, the immediate investigation did not reveal any particular malfunctions or damage. All accelerations recorded on the site were within a range of 0.017 to 0.047 g, more than 6 times lower than the design-basis level. No recordings exceeded the 0.05g threshold of the inspection earthquake depending on the horizontal component.

However, one sensor did record a vertical acceleration level that exceeded the additional inspection threshold of 0.033 g: 0.037g. It was decided to shut down Cruas’ three operating reactors for this reason. They were gradually shut down in the evening of 11 November 2019.

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[11] In the reactor building, in the auxiliary building and on the ground (free field).

[12] The value based on the vertical axis is peculiar: if we usually consider that by design, the vertical component of seismic movements is equal to 2/3 of the horizontal component, nothing indicates that the sensitivity of structures and components is greater depending on the vertical axis (post-seismic operating experience actually suggests the contrary). Plans are in place to remove this 2/3 coefficient from procedures.

Subsequently and as per the procedure, EDF conducted an in-depth investigation. The report was prepared in line with international best practice (IAEA[13] and EPRI[14] guides), after which it was sent to the regulator about ten days after the event and reviewed by the IRSN for approval to restart. The report did not identify any damage that could be ascribed to the earthquake. The regulator carried out two inspections and granted EDF approval to restart on 6 December. The reactors were gradually connected to the grid over the period of 7 to 13 December.

d. Lessons for the future

The Le Teil earthquake that occurred on 11 November 2019 is the most powerful earthquake to have been felt on a French NPP since the Sierentz earthquake on 15 July 1980, 25 km away from Fessenheim NPP. With a magnitude of 4.7, it exceeded the 0.01g threshold (0.014g recorded at the time).

The Le Teil earthquake is largely covered by the design assumptions of Cruas NPP, the first in the world to be built on earthquake-resistant bearing pads.

The main lessons learned from the plant's response will help to improve post-earthquake plant operating procedures (improving short and medium-term inspection measures), to verify structure design tools and models, particularly for structures built on earthquake-resistant bearing pads and to better characterise the harmfulness of earthquakes of this type (moderate magnitude, close to the site) on nuclear facilities subjected to an extensive seismic design process and well-documented operational monitoring. Some of the aforementioned topics will probably be covered on the occasion of international benchmarking sessions in order to share operating experience with the whole of the scientific community.

Plans are also in place to learn lessons from this earthquake with regard to the evaluation of seismic hazards, taking account of a new event of this type using different methods, depending on whether a deterministic or probabilistic approach is adopted. In this way, probabilistic insights may be provided on the effect of translocation under the site (application of RFS 2001-01) in terms of return period[15]. More generally speaking, methods for comparing observations across a region (Bayesian method, for instance) can be used to verify the consistency of probabilistic results with all observed seismicity, thereby justifying the agreed hazard levels[16].

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[13] International Atomic Energy Agency

[14] Electric Power Research Institute (USA)

[15] It is possible to determine the event's return period as recorded on the Cruas site (ground acceleration in the range of 0.02 to 0.05 g for an epicentral distance of approx. 10 to 15 km) by using the results of available probabilistic safety analyses, resulting in a return period ranging from 300 to 1000 years. It is then possible to evaluate the return period of this epicentral acceleration at Cruas (ground acceleration assumed to be a few tenths of g for an epicentral distance of zero) based on the results of the same probabilistic safety analysis: it ranges from 25 000 to 200 000 years. This illustrates the effect of translocation under the Cruas site of an earthquake such as the one of 11/11/2019 in terms of the associated acceleration return period.

[16] Readers may refer to the conclusions of an OECD workshop on this very topic: www.oecd-nea.org/nsd/docs/2015/csni-r2015-15.pdf

Conclusion

Seismic risk management on nuclear facilities lies at the meeting point of two major sciences:

a) Geology and seismology which analyse and characterise earthquakes as natural phenomena. This branch of natural science has its own language and techniques. It characterises seismic events by the movement of geological faults, their magnitude, their depth and the propagation of seismic waves in the Earth's crust.

b) Engineering science and seismic engineering which, based on postulated ground movement in a given place, expressed in engineering terms as acceleration and response spectrum, design and demonstrate structural resilience. That is why, in the event of an earthquake like the one that occurred at Le Teil, readers and listeners may be surprised that the data, the rationale and the positions are expressed in the form of parameters as different as magnitude or acceleration. The latter alone describes the vibrations felt by a facility and the scale of its severity in the light of its design.

From a seismological standpoint, the Le Teil earthquake is not a novel occurrence in the Rhone Valley. Nor is it a surprise, given that it is of the same nature and scale as earthquakes regularly observed throughout the history of the Rhone Valley. Its most unusual feature, not unknown in this region, is the shallowness of its seismic source. That is why this earthquake of a moderate magnitude caused surface ruptures of about ten centimetres, phenomena which are usually caused – worldwide – by markedly stronger earthquakes.

On the sites of nuclear facilities, the Le Teil earthquake only caused minimal accelerations, well below those considered for their design, and did not adversely affect plant components. This is not surprising insofar as the measured spectrum is well below the design-basis spectrum: the geological event is of the same scale as that which, by adding a margin, forms the basis of current reference standards; the quake recorded on the sites was attenuated by distance; very wide margins were built into the different phases of nuclear plant design.

The key parameters of this earthquake (location, fault slip, magnitude, depth) were established in the days, weeks and months that followed it. The results were gradually fine-tuned and the various methods converged. Large amounts of data still need to be processed, making it possible to specify and validate the seismological models and techniques.

From a nuclear-safety perspective, operating experience firstly concerns investigation procedures used in the event of an earthquake, these procedures needing to be finetuned and made more direct and ready for immediate use. As is always the case in similar circumstances, the design basis for facilities located in the geological area of this earthquake will be reviewed in detail. This will include an examination of faults around the sites, the potential for surface ruptures, near-field movement characterisation and harmfulness, etc.

Issued nearly 20 years ago, the deterministic Basic Safety Rule (RFS) has proven to be robust and has fulfilled its role. It is now being supplemented by probabilistic seismic hazard analyses which are widely used around the world and which are now being increasingly used in France.