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Reduction of excavation face collapse risk in tunnelling

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Summary

Background: *Two large road tunnels, recently developed near Florence, showed instabilities of the excavation face which subsequently caused sixteen collapses. Due to the risk for workers' safety, the public authority for occupational health and safety (ASL) has monitored the failure rate and other background variables in order to assess the possible correlations between risk reductions, its own actions, and those of the various safety actors involved.* **Objectives:** *To evaluate if the interventions carried out by the design team were able to reduce the risks of collapse and which of the ASL actions and/or which other factors were more effective in changing the attitudes of the parties involved, leading to a more expensive but safer project variant.* **Results:** *After adoption of the second of two project variants, no more collapses were observed. No correlation was found between trend of ASL inspections and observed variation of collapse rate. Conversely, the adoption of strongly coercive measures and investigation reporting by local media coincided with periods of risk reduction, even if the low number of events does not allow for statistical evaluation.* **Conclusions:** *These findings appear to be coherent with the ratio of the cost of penalties related to health and safety infringements (thousands of euros) to the overall cost of the safer project variant (a hundred times greater). The safer variant required 7% more labour but avoided forced interruptions caused by the collapses, allowing a 13% faster excavation rate.*

Riassunto

«Riduzione dei rischi di crollo nello scavo di gallerie». **Introduzione***: Due grandi gallerie stradali recentemente realizzate nei pressi di Firenze hanno mostrato instabilità dei fronti di scavo, con 16 crolli. Dato il rischio per la sicurezza dei lavoratori, l'ASL ha condotto i suoi interventi monitorando i crolli ed altre variabili di contesto, per valutare l'effettivo miglioramento della sicurezza.* **Obiettivi***: Valutare se le varianti introdotte dal team di progetto hanno realmente ridotto il rischio di crollo, e quali fra le azioni ASL ed altri fattori sono stati più efficaci nel cambiare gli atteggiamenti degli attori coinvolti, portandoli ad accettare una variante di progetto più costosa ma più sicura.* **Risultati:** *Dopo l'adozione della seconda variante del progetto non si sono più osservati crolli. Non si rilevano correlazioni tra la quantità di ispezioni eseguite dall'ASL e le variazioni osservate del rischio di crollo.L'adozione di misure fortemente coercitive come i sequestri, così come la comparsa di notizie sui media locali, presentano concomitanze temporali con fasi di riduzione del rischio, anche se il ridotto numero di eventi non permette una valutazione precisa.*

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Conclusioni: *Tali risultati possono considerarsi coerenti con il basso rapporto tra l'onere delle sanzioni in materia di sicurezza del lavoro (dell'ordine delle migliaia di euro) e i costi aggiuntivi imposti dalla variante di progetto più sicura (centinaia di migliaia di euro). La variante più sicura ha richiesto un aumento del 7% della manodopera ma, evitando le interruzioni del lavoro dovute ai crolli, ha ridotto del 13% i tempi di realizzazione dello scavo.*

Introduction

The major road infrastructures recently built around Firenze (Florence, It) include tunnels excavated by sequential method. Tunnelling work is associated with high injury rates, and one specific hazard is the instability of the excavation (14), that in particular conditions may collapse, causing economic losses and possible damages and/or injuries.

The ASL (OSH public health authority) prevention services include workplace inspections aimed at identifying health and safety risk factors and, subsequently, at indicating mandatory measures to eliminate them, in order to ensure compliance with laws and technical standards requirements.

Information collected in the early inspections showed that two of the tunnels were problematic, due to the large section and poor geomechanical rocks' characteristics. An initial collapse of the excavation face, also causing injury to one worker, occurred two months after the beginning of the work. Two more collapses, without injuries, occurred in the following month. This was just the beginning of a long chain of similar events that continued, despite a large number of on-site inspections, mandatory technical prescriptions, and a temporary seizure. Only the later adoption of a second project variant seemed to eliminate the problem.

We tried to evaluate the effectiveness of the different measures applied in terms of reduction of the ratio between the number of collapses and meters of tunnel excavated, with the aim to suggest the most promising intervention policy to adopt in the future.

Methods

Notes on excavation technique

The excavation was carried out full section, in sequential phases, cyclically repeated. Initially, the rock mass is reinforced by inserting and grouting long glass fiber reinforced polymer (GFRP) pipes, then dug for a predetermined length (so-called "excavation field", typically 3-12m long) and stabilized with metal ribs and shotcrete. After completion of each field, the sequence starts again. Considering same gallery size and geomechanical properties, the main parameters that determine the stability of the excavation face – indicated in the excavation project – are the number and length of GFRPs, the length of each "field" (the shorter, the more stable), the section and distance of steel ribs, and the thickness of shotcrete linings. Sizing them is a delicate search for an optimal equilibrium. Undersizing increases the chance of collapse (and high expenses in case it occurs), whereas oversizing increases costs for materials and labour. For more details, see supplementary material.

In the tunnels considered, the sequential excavation method was applied almost everywhere. An early version of the project was adopted for the first 329 meters. A revised project was then applied for 1547 meters, followed by a second and last revision adopted in the remaining 1387 meters.

Evaluation methods

The collapse rate was calculated as the ratio of the number of failures occurred to the length of the excavated tunnel.

All injuries occurring inside the tunnels (total number=76) were individually examined, but only one was directly related to the collapse of the excavation front, in a situation – additionally – not comparable to other collapses. Therefore, a relative injury rate could not be evaluated, and we decided to evaluate risk through the observation of incidents rather than injuries.

The assessment of support under-sizing as a possible cause of collapses was based on the finding that the stability of the front decreases as the excavation progresses through within each field. Therefore, we considered the placement of the collapses within the "excavation fields", checking if the distribution was more compatible with the predominance of unexpected and purely random factors or as an effect of the progressive demolition of undersized pre-support GFRPs.

An initial evaluation of the impact of ASL inspections was based on the observation that the excavation works went through two periods with different risk magnitude. We compared the frequency of the inspections in those two phases. A second purely qualitative assessment was based on the examination of temporal overlap between the evolution of subsidence phenomena, the adoption of specific coercive measures by the supervisory board and the investigation reporting by the local media.

Finally, we examined the plausibility of some explanatory hypotheses about corporate behavior, based on economic implications inferred by the amount of hours worked in different periods.

Sources of data and methods

Both ASL and the main contractor adhere to the "Infomonitor" information system (www.infomonitor.it), that collects all detailed data about hours worked (monthly), injuries occurred, data collected during on-site ASL inspection and consequent penalties and prescriptions. ASL has collected other information (e.g. details on each collapse, data about rock mass type, etc.) during further investigations.

We carefully examined data on collapses with regard to the possible initial causes, the magnitude of each event and the reliability of data sources. For each collapse, we checked whether it occurred in connection with infringements of the project plan's work methods, or despite complying with them. The first contingency applied only to the first crash that occurred at the resumption of work after an unforeseen standstill. This stoppage lasted much longer than allowed for in the project, thereby reducing the rock mass stability below expected parameters. For this reason, this event was considered not comparable to the others and was therefore excluded. Regarding the magnitude of the collapses, it was evaluated that the volume of material released was not decisive for inclusion or not, since even a small failure indicates a deviation from the expected standard and lack of control in the production process. We excluded only marginal failures, corresponding to four minimal releases (<1 m^3, compared to a maximum of 900 m^3) and two more events occurred as crackings in the shotcrete lining, without release of material.

We also considered the divergence of interests between the parties involved in the planning and in execution, as both parties might find it convenient to attribute responsibility and corresponding failure costs to the other. We checked all contradictory data between the design team and the building contractor. Only two events were in conflict, both relating to marginal releases (<1 m^3) and as such, already excluded from the assessment.

In both galleries the collapse trend was similar and well correlated to the excavation length (R^2=0.7). Galleries were geographically very close, the building company was the same, as was the project team, and the project parameters (size, rock mass classification, calculation method) were almost identical. As a result, the adaptation of the second tunnel project was based on the experience gained in the first. Given that overlap, we examined both the situation of each single tunnel and that derived by their sum (events and excavation length), in order to enlarge the sample sizes and obtain a more reliable assessment.

Media analysis started only after a first local TV news report and a newspaper coverage on tunnel collapses and seizure. Following the last collapse (extended up to the surface and occurring near an ancient home) the media coverage greatly increased focusing not only on workers' safety but also on the consequences of forced work stoppages such as layoffs, and risks for historical and residential buildings.

The set of monitored items is listed in supplementary materials, Table A and Table B.

Statistical methods

The risk of collapse, expressed as number of collapses per length of excavation, was compared across the various sections of the excavation work. We calculated rate ratios and their confidence intervals by means of Poisson rates, using "R" software, version

3.3.2. For the three-sided comparisons, we applied the Bonferroni coorrection: in order to get an overall significance level of 5% we considered in each single comparison a significance level of 0.05/3=0.0166.

We evaluated the probability of occurrence of a certain concentration of collapses in a pre-determined section of each excavation field by means of a binomial distribution. Assuming that collapses originate only from random factors, their location within the length of the excavation fields should be neutral. Ideally, after dividing each field into three sections of equal length the probability that a collapse occurs in the initial, middle or final part of the field would be identical and equal to 1/3. The probability of observing a certain number of collapses in a determined section of the field is:

$$(1)\ P(k) = \{n! / [k! \cdot (n-k)!]\} \cdot p^k \cdot (1-p)^{(n-k)}$$

Where 'p' is the probability of collapse in a determined section, 'n' is the total number of collapses examined and 'k' is the considered number of collapses in a certain section of the field. Consequently, the probability of observing k' *or more* events concentrated in a determined section of the fields equals the sum of probabilities for k ranging from k' to n:

$$(2)\ P(k \geq k') = {}_{(k' \ldots n)}\Sigma \{n! / [k! \cdot (n-k)!]\} \cdot p^k \cdot (1-p)^{(n-k)}$$

Results

Effects of rock mass type variations

The possible effect of variation in rock mass type was evaluated in correspondence with the 16th failure, when the work had reached just about the midway point. The excavation encountered unstable "Sillano" rock (RMR class V - Very poor rock) (4), and more steady "Monte Morello" rock (RMR IV) (4). Excavation in "Sillano" was carried out in fields ≤9 m length with mean progression around 0.7 m/day. Monte Morello was excavated in longer fields (sometimes over 10 m) and two trunks in unsupported continuous excavation, typically advancing at 1.1 m/day.

At the time of this evaluation, the excavation length in "Sillano" was 1447 m, with 10 collapses (one every 144.7 m), and in "Monte Morello" was 397 m, with 4 collapses (one every 99,25 m). Two remaining collapses occurred in transition zones, hence not being clearly attributable to one specific rock type. Risk of collapse was lower in "Sillano" (RR=0.69, CI=0.20-3.00; p=0.12).

At the very end of the work, total length in Sillano reached 2755 m with 10 collapses, and Monte Morello 508 m with 4 collapses. Risk was lower in "Sillano" (RR=0.36; CI=0.10-1.57; p=0.09).

Effects of project variants

Linking the relevant failures (labeled "A" and "B" in supplementary materials, Table A) with the simultaneously realized excavation length, we obtained the graph in figure 1, which also shows the overlapping with the project's three subsequent variants. The failure rates, expressed as ratio between number of collapses and length of excavation, were compared across the various versions of the project, considering either each single tunnel or the sum of the two. Results are summarised in table 1.

Undersizing of face pre-support

Given the importance of design factors, we evaluated if pre-support undersizing could explain the collapses. The progress of the excavation involves the gradual demolition of the reinforcements applied at the beginning of each excavation field, progressively diminishing stability while the excavation front approaches the end of the field. If the initial consolidation was insufficient, core cohesion may get too close to its resistance limit, and the inevitable random fluctuations of the various parameters may possibly lead to exceeding this limit, causing a collapse. The probability of such an occurrence increases as excavation advances into each field. Under this hypothesis, collapses would concentrate in the final part of the fields. We tested it against the null hypothesis (H_0=collapses originated only by random factors and neutrally distributed along each field) by means of equation (1).

Considering the 14 events that can be exactly positioned in their "excavation field" (classified as "A" in suppl. materials, table A), three of them occurred in the initial section of the excavation field, two in the central and nine in the final. The probability of

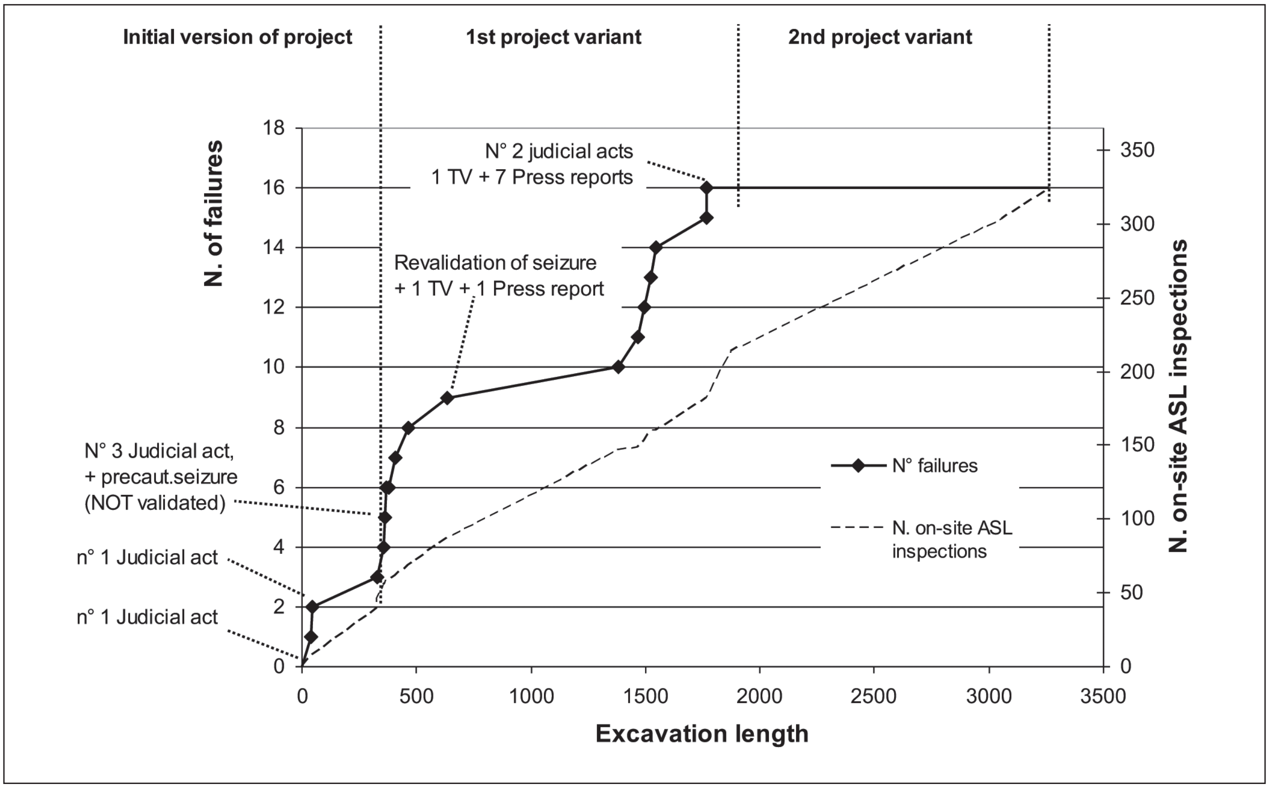

Figure 1 - Excavation length, number of failures, ASL inspections, judicial acts, and other context variables

observing this concentration, according to equation (2) is ΣP (k)=0.017.

We can then reject H_0 (p>98%) and accept the alternative hypothesis, that collapses are derived from factors closely related to the advancing of the excavation within each field, such as the progressive weakening of pre-support systems already undersized at the origin.

Correlation between ASL inspections and risk reduction

The main actions carried out by ASL consist of on-site inspections. In case of violation of safety regulations, penalties and mandatory technical provisions follow. If violations are repeated or related to particularly serious risks, all or part of the activities, e.g. the excavation front, can be seized.

We wondered whether inspections alone were able to reduce the levels of risk. Archive recordings showed that in the high-risk period (initial project and first variant) the inspections were 214 in 1,302 days (one every 6.08 days). In the following safer period, inspections were 110 in 588 days (one every 5.35 days). This minimal difference fails to suggest that change in the frequency of inspections affected collapse risk. For more details, see supplementary materials.

Correlations between judicial acts, context variables and risk reduction

We wondered whether and which other ASL actions could have been effective, at least indirectly, in influencing counterparts' decision to adopt the safer 2nd project variant. The uniqueness of this experience did not allow for an analytical / quantitative answer. Some suggestions were offered by the overlapping between variations of collapse risk, execution of inspections, issuing of legal acts and context variables, shown in the graph in figure 1. We highlight some coincidences:

Table 1. Comparison of failure rate in various project versions

Tunnel	Project version comparison	A Excav. length [m]	A Failures	A Rate F./m	B Excav. length [m]	B Failures	B Rate F./m	Comparison [A] vs. [B] RR [A]/[B]	98.3% C.I. for RR (*)	p
Tunnel 1 alone	1st variant (A) / Initial (B)	1362	9	6.61	329	3	9.12	0.72	0-4.89	0.42
	2nd variant (A) / Initial (B)	911	0	0	329	3	9.12	0	0-1.05	0.02
	2nd variant (A) / 1st variant (B)	911	0	0	1362	9	6.61	0	0-0.86	0.01
Tunnel 2 alone	2nd variant (A) / 1st variant (B)	487	0	0	513	4	7.80	0	0-1.17 (95%, **)	0.07
Sum of both tunnels	Initial (B) / 1st variant (A)	329	3	9.12	1875	13	6.93	1.32	0-4.88	0.44
	2nd variant (A) / Initial (B)	1388	0	0	329	3	9.12	0	0-0.69	0.01
	2nd variant (A) / 1st variant (B)	1388	0	0	1875	13	6.93	0	0-0.50	0.001

(*) For three-sided comparisons (three project variants applied in tunnel 1 alone and in sum of both) the 98.3% c.i. is indicated, so to obtain, according to Bonferroni, 95% global significance of contemporary comparison.
(**) For the two-sided comparison, only regarding the two project variants applied in tunnel 2, no correction is needed to the 95% c.i.

- Periods of risk reduction are observed after the second release of prescriptive acts, after the validation of the seizure and after the third series of prescriptive acts;
- No risk reduction is observed after issuance of acts and seizure not validated by the judicial court;
- Periods of risk reduction are observed after newspaper and TV news reports;

Comparison of variable costs of excavation and amount of penalties

Building on preceding findings, we wondered whether the lack of short-term effects related to inspections was compatible with the interests of the parties to maximize their economic return, which could induce them to minimize the costs, such as those related to penalties. Available economic data allows us to compare the costs of penalties and those necessary to prevent the collapses, at least in terms of magnitude.

As regards specific activities of pre-support and excavation, total labour costs for the over 400,000 hours worked can be estimated at around € 10 million (8), possibly corresponding to no more than 25% of the total cost (art. 118 c. 6-bis of D.Lgs. 163/2006 "Italian Code of public contracts" and agreement of 28/10/2010), the other 75% being attributable to materials and equipment. On these bases, we can reasonably argue a total cost of about €40 million, variable within an ample margin, depending on project choices. Therefore, the adoption of safer project solutions, such as shorter digging fields or stronger face pre-support, may result in price increases around € 400,000 for each percentage point increase of such specific works.

In comparison, the typical cost of penalties lies in the order of some thousands euros, and the probability of receiving one is low: there were 318 inspections focussing on excavation stability problems, with only 6 penalties (less than 1 every 50 inspections) and 1 seizure applied.

The accuracy of these estimates is questionable, but the disproportion of two orders of magnitude between the cost of implementing lawfully compliant safety measures and the cost of penalties is grounded.

Medium term economic notes

Table 2 shows, for the three variants of the project, data on average productivity in meters per day of each excavation front, labour productivity in hours worked per meter, and excavation stoppages caused by collapses, expressed as number of days in which the excavation front could not advance, since all activity was aimed at restoring the damage caused by the collapse.

Productivity of labour follows an irregular pattern. Comparing the last and safer version of the project to the sum of the two riskier initial periods, each meter excavated required 7.3% more working hours.

The excavation advanced faster with the project safer version. In particular, mean daily productivity of the excavation fronts improved of about 13%. Presumably, this result was due to the absence of long lasting interruptions of the advancement due, in the initial versions of the project, to the repeated collapse of the front, causing about 1/4 of excavation front activities to be lost.

Discussion

Observational studies are the only tool to evaluate the effectiveness of actions like inspection, mandatory technical prescription, precautionary seizure and public opinion impact in a context where an experimental study cannot be applied (3).

The scarce influence of rock mass type on the collapse risk observed in this study suggests concentrating efforts on preventive actions rather than on the analysis of geological conditions. According to Italian laws, "*…Workplaces and passageways must be suitably protected against…collapse of materials…*" regardless of boundary conditions as, in this case, the higher or lower stability of the rock mass. The absence of significant risk difference, the excavation in longer fields and the achievement of higher excavation productivity in correspondence with the steadier rock mass type, suggested that the project model had predictive power, but also that such capability was exploited more to raise productivity rather than to reduce risk.

No collapses were observed after the adoption of the 2nd version of the project variant, whereas no reduction was observed between the initial project version and the 1st variant. Factors that were able to influence the behaviour of the building contractors include:

- Legally binding measures such as prescriptions, or even more coercive such as seizure.
- Press and TV reports had a certain impact on the public image of the subject. Topics referring

Table 2. Mean daily productivity of excavation fronts, manpower requirements and work stoppages (sum of both tunnels)

Project version	A Excavation length [m]	B Hours worked (× 1000)	C Excavation fronts activity (days) *	D = A/C Mean daily productivity of exc. fronts (m)	E = B/A Hours worked per meter excavated	F Excavation stoppages days (**)
Initial project	329	131	555	0.59	398	155
1st proj. variant	1547	382	2270	0.68	247	600
Total of riskier period (init. project + 1st variant)	1876	513	2825	0,66	273	755
2nd proj. variant	1387	407	1846	0.75	293	0

(*) C = Σ (n° active excav. fronts) × (n° days of activity)
(**) F = Σ (n° of idle fronts) × (n° days stoppage of excavation advancement)

to structural safety of houses and employment consequences of work stoppages may have been more effective in arousing attention, compared to those related to worker's health and safety.

- Inspections alone with no judicial follow-up did not seem relevant, at least in the short term. This notwithstanding, many of the surveys, supplemented by intensive acquisition and study of technical documentation, were indispensable in identifying the problems at the origin of the collapses, clarifying possible legal infringements and defining coercive measures. These procedures were both useful for problem solving and firmly sustainable in court, thereby probably contributing to the adoption of the safer 2nd project variant.

The disproportion between the amount of possible fines and the much higher additional cost of labour and materials needed to apply safer design parameters, suggests that, at least in the short term, it might be considered economically preferable to avoid investing a significant share of resources to reduce "a priori" the probability of penalization by the supervisory body (ASL) and to adopt corrective actions "a posteriori", i.e., only if and when an enforcement act is actually issued.

This does not necessarily mean that various stakeholders do not care about risks and injuries. On the contrary they often do, even sometimes exceeding legal requirements, e.g. (2), but this mainly depends on "internal" reasons, like corporate image, leaving a very marginal importance, if any, to the external factor "cost of possible penalties".

Considering the entire work, the cost impact of higher labour requirement related to the safer variant could be offset by the savings due to reduction of completion time.

Given the uniqueness of this experience, these indications remain for now largely uncertain, yet they represent aspects worthy of further study and consistent with literature findings that "…general deterrence is less effective in reducing injuries, whereas specific deterrence with regard to citations and penalties does have an impact…" (10, 11).

The absence of effectiveness of the simple "inspection", as well as the disproportion between cost of fines and of building companies investments in occupational safety, shows similarities to that found in previous estimates in the traditional building sector (1).

The role of the media in improving construction safety has been addressed (9) but deserves further investigation. The ongoing declining trend of injury rates (5) calls for a better understanding of the interactions among all involved parties that could lead to a further decrease of injury rates.

In conclusion, our investigation suggests that:

- The observation of accidents without injuries allows measuring changes in risk even where the number of injuries is extremely small;
- The measure of risk becomes more reliable by tightly defining the phenomena under investigation (here, the "collapse of the excavation face");
- Intervention policies based on large number of inspections with little technical insight are of little use to reduce risk level. It is better to carry out a smaller number of "intensive" interventions, aimed at the effective improvement of a few real priorities;
- In order to be effective, inspections and related activities require a high level of technical knowledge. This becomes even more essential in court litigation when particularly stringent, expensive and technically complex measures are involved;
- Particularly in the case of intervention of major importance, media involvement should be considered.

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