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The impact of seismic events on human reliability and Phoenix HRA methodology

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Abstract:
Risk assessment of Nuclear Power Plants (NPPs) through Probabilistic Risk Assessment (PRA) and Human Reliability Analysis (HRA) is relatively mature for internal events – those that start inside the power plant it serves. Advances have also been made for external events, such as earthquakes and floods. Yet, particularly for HRA, more research is needed to understand the impact of seismic events on human performance and the adequacy of currently used HRA methods. According to a report from the International Atomic Energy Agency, around 20 percent of nuclear reactors worldwide operate in areas vulnerable to earthquakes, so understanding seismic impacts on HRA is significant to prevent human errors and for realistic Human Error Probability (HEP) assessment.

Seismic events may add failure modes and human and organizational factors that are not fully addressed by internal event models. This paper will investigate the unique factors associated with seismic events, and how they can be incorporated in the Phoenix HRA Methodology.

Keywords: Human Reliability Analysis, Seismic Events, Phoenix HRA, Nuclear Power Plants

1. Introduction

In the wake of the Fukushima accident, there has been a renewed interest in analyzing external events, especially seismic events, and how they affect human error and can be modeled in a PRA. Seismic events affect human reliability by, for instance, introducing additional stress or workload and causing physical damage to the plant from the earthquake itself or resulting events like aftershocks, fire, or floods.

Existing research incorporating external events into HRA has been conducted by various groups and contains a variety of insights that are built upon in this paper. Early assumptions contained a wide range of HEPs—anywhere from 5-30 times higher than those calculated for internal events. (Park et al. (2019)). Chatri et al. (2018) outlined many challenges resulting from seismic events HRA and investigated creating an overall HEP multiplier. They concluded that the factors necessary for developing a multiplier were the location of the task (inside or outside the main control room), the time available for the task, and the seismic intensity. Park et al. (2015) also utilized seismic intensity to estimate HEP and reaction times for human operators, and yielded an HEP multiplier range for different seismic scenarios. Kirimoto et al. (2021) identified the importance of creating a qualitative HRA model that included factors that affected task performance in addition to traditional quantitative methods, incorporating Performance Shaping Factors (PSFs) into the external events HRA. Kang and Seong (2022) developed a PSF taxonomy for extreme external events, improving on the limitations of existing taxonomies from HRA models such as THERP. SLIM, and SPAR-H.

Phoenix is an HRA methodology that is based on the Information, Decision and Action in a Crew context (IDAC) cognitive model to model operator performance (Ekanem et al. (2016)). It incorporates strong elements of existing HRA methods and cognitive science, and was initially developed for internal events performed in a control room. Yet, its framework and elements are suitable for external events such as earthquakes.

This paper analyzes Phoenix elements according to i) completeness – i.e., are all aspects involved in human performance during seismic events represented in Phoenix? and ii) adequacy – i.e., how well do Phoenix elements reflect human performance during seismic events?

The paper is organized as follows. Section 2 provides an overview of existing HRA methods used to analyze seismic events and notes limitations of the current methods. Section 3 presents an overview of the Phoenix HRA methodology, identifying the layers of the model. Section 4 describes proposed modifications to Phoenix in order to model seismic events, building on existing HRA seismic research. Finally, Section 5 describes concluding thoughts and areas where further research must be conducted.

2. HRA and Seismic Events

2.1 HEP multipliers applied to internal event HRA

One principal method for incorporating seismic events into an HRA involves multiplying the HEP found using an existing internal event HRA with a numerical multiplier that is based on one or more factors present in a seismic event. Early models estimated the value of these multipliers to be anywhere from 5-30. Later models made the case that the HEP would be linearly dependent on seismic intensity, i.e. the higher the intensity of the earthquake, the greater the impact until a certain upper limit HEP ((Park et al. (2019)).

Models of this form were then expanded to include task complexity and available time in addition to seismic intensity as shown in the HEP multiplier model in Fig. 1.

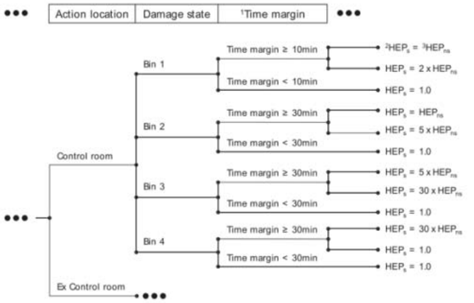

Fig. 1: Decision tree for calculating an HEP multiplier given seismic intensity and time margin of task completion. Park et al. (2019).

2.2 Incorporation of other parameters including PIFs

There has been research done towards creating a full model that can conduct more representative HRA with seismic events, but due to the amount of factors affecting human error, there have been challenges implementing a complete methodology. “Assigning more representative HEPs for the human actions following the internal and external hazards would prove to be tedious as this should take into consideration many parameters that may not be easily quantifiable. These would include the consideration of the different stress levels, habitability issues, the degree of operator training and operator readiness to react in a proper manner” Chatri et al. (2018). Kirimoto et al. (2021) expands upon this, stating that “it is necessary in HRA to identify a realistic context for qualitative analyses, which thus points out the importance of […] representing how tasks in an accident scenario are affected by various factors, such as plant conditions (speed of accident progression, equipment availability, etc.), operational procedures including cognition, and human-machine interfaces.” All of the examples brought up in these studies are PIFs, which should be incorporated in performing calculations.

As a starting point toward developing an external event HRA model, Kang and Seong (2020) developed a new PIF taxonomy to be used. We will conduct a thorough comparison of the PIFs they identified with PIFs already present in the Phoenix model in Section 4. Kang and Seong included in their report that, although a suitable HRA model does not exist yet, their taxonomy can be utilized in the creation of an extreme external events HRA model.

3. Phoenix HRA Methodology

Phoenix is a model-based HRA methodology originally developed for NPP control room operations. Phoenix is structured in a series of layers, as illustrated in Fig. 2. The principal parts of the Phoenix model that will be investigated in this paper are Crew Response Trees (CRTs), Fault Trees that delineate Crew Failure Modes (CFMs), and Bayesian Belief Networks (BBNs) that model the impact of PIFs into CFMs.

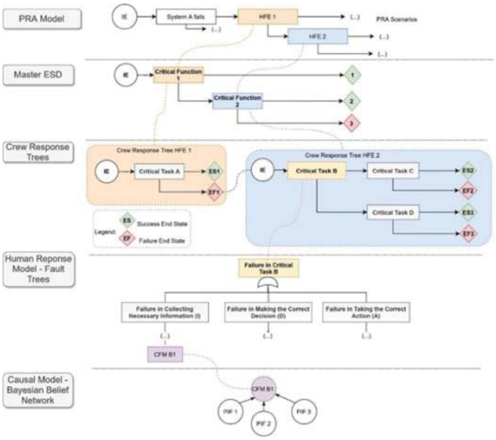

Fig. 2. Phoenix Methodology and Relation to PRA Model. Ramos et al. (2021).

Within Phoenix, the CRT visually represents crew-plant interaction scenarios that lead to HFEs and a provide a structure for the qualitative analysis in lower levels. The CRTs are developed to model Human Failure Events (HFEs) corresponding to a Critical Function (CF). In the CRT questionnaire, questions guide the addition of branches and the existence of Branch Points (BPs). In the CRT we also obtain the Critical Tasks (CTs), whose failure is modeled by the fault trees.

The crew's failure in performing the CTs identified in the CRT is further modeled using FTs to identify the relevant CFMs. Phoenix FTs were developed to bridge the gap between HRA and psychology/human factors.

Phoenix PIFs are organized on a hierarchical structure containing three levels. Level 1 PIFs directly impact the CFMs, while Level 2 PIFs impact Level 1 PIFs, and Level 3 PIFs impact Level 2. Phoenix has 8 Level 1 PIFs: Knowledge/Abilities and Bias, which map to cognitive response, Stress, mapping to emotional response, and Procedures, Resources, Team Effectiveness, Human System Interface (HSI), and Task Load, which map to qualities in the physical world. The PIFs are assessed in two "states", corresponding to a nominal or degraded effect on crew performance.

4. Phoenix and Seismic Events

This section presents the proposed modifications on Phoenix to better model seismic events. The impact of seismic events on human error is associated with the seismic magnitude scale and damage states, and is modeled in two layers of Phoenix. First, a component is added to the HFE FT: depending on the damage state, the crew has insufficient conditions for performing the task. Second, in case tasks are feasible, a probability of insufficient workplace conditions due to seismic damage (e.g., instrumentation is damaged and does not provide information to the operator) is modeled through the I, D, and A FTs. Third, the indirect impact of seismic events is modeled through the PIFs, such as stress, and resources.

4.1 *Damage States*

The impact of seismic events on human performance depends on the seismic magnitude scale and its impact on the plant. We adopt EPRI's definition of Damage State, as shown in Table 1:

Table 1: Damage stage definitions. EPRI (2014).

Damage state bin #	**External Event Damage State Description**
1	No damage to the plant safety-related SSCs or non-safety SSCs required for operation. Limited damage to non-safety, non-seismic designed SSCs like residences and office buildings.
2	No expected damage to the plant safety-related SSCs or to rugged industrial type non-safety SSCs required for operation. Damage may be expected to non-safety SSCs not important to plant operations and to the switchyard (e.g. LOOP expected). Some falling of suspended ceiling panels.
3	Widespread damage to non-safety related SSCs and/or some damage expected to safety related SSCs. Significant number of vibration trips and alarms requiring resetting.

Damage state bin #	**External Event Damage State Description**
4	Substantial damage to safety related and non-safety SSCs. This is particularly applicable to external events susceptible to a cliff-edge effect.

Park et al. expanded the definitions of EPRI detailing the effect of the damage states on the response time of control room operators (Table 2):

Table 2: The context of each damage state (DS) and its effect on the response times of MCR operators. Park et al. (2019)

DS	**Information available in MCR**	**Stress level in MCR operators**
1	Indicators for monitoring: OK Indicators for conducting EOPs: OK Alarms: OK	Similar to an incident without a seismic event
2	Indicators for monitoring: a couple could be failed Indicators for conducting EOPs: OK Alarms: a couple could be failed	High stress level in early phase due to psychological shocks. Effect of shock lowered after a couple of hours
3	Indicators for monitoring: most show misleading info Indicators for conducting EOPs: a couple could be failed Alarms: most give wrong information	Higher initial stress level than at damage state 2.
4	Indicators for monitoring: complete failure Indicators for conducting EOPs: complete failure Alarms: complete failure	Extreme stress level

4.2 *Direct impact: Fault Trees and CFMs*

In Phoenix, the CFMs follow the IDA cognitive model – Smidts et al. (1997)- the crew may fail to perform a critical task if they:

(i) Fail to gather correct information, fail to understand or pre-process the collected information (I)
(ii) Fail in situation assessment, problem-solving, and decision-making, even after gathering correct information (D)
(iii) Fail during the execution of an action, even after having made the correct decision (A)

Seismic events are an additional factor leading to the HFE, as shown in Fig. 3. If the damage state is 4, there are no conditions for operators to perform their tasks, independently of how they perform information gathering, decision-making and action taking, and this event received the probability of 1. The probability associated with other Damage States is subject to further investigation.

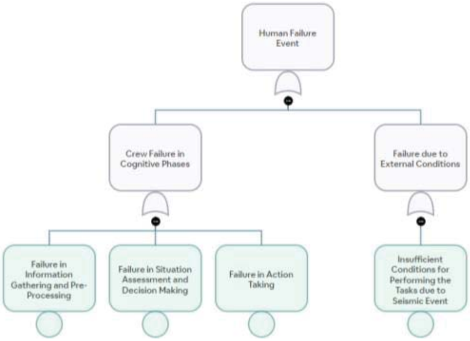

Fig. 3: Fault Tree including HFE due to Insufficient Conditions for Performing the Tasks.

The event of “insufficient conditions for performing the task dues to seismic event” can be treated as a “feasibility” factor, adopting a value of one when the task is unfeasible and of zero if the task is feasible. It can also be modeled probabilistically, adopting a probability value that depends on the damage state.

We also propose modifications to the Fault Tree associated with Action taking. If operators, either individually, or as a team, decide to evacuate the plant due to a seismic event, there may not be enough people available to accomplish the action. The probability of this specific scenario during a seismic event must be investigated.

Finally, we propose adding the CFM “No Action” as shown in Fig. 4. This is aligned with Al-Douri et al. (2022) who proposed the fourth CFM in the Action group, “Action on an Object or Component not Being Performed”.

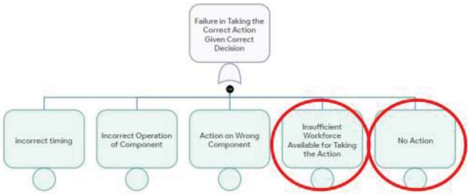

Fig. 4: Fault Tree including CFM due to physical impact of seismic events.

4.3 *Indirect impact: PIFs*

Seismic events indirectly affect human performance through PIFs. A greater magnitude seismic event leads to more severe environmental conditions and site damage, which in turn influences certain PIFs, including workplace adequacy, tool availability, HSI, stress, task load, and team factors. Chatri et al. (2018) state that "during the seismic event, the operator faces a complex situation due to the supplementary stress caused by the earthquake itself, random damage of systems and components, possible blockage of the seismic route, possible induced fires and floods, aftershocks, and likely impaired communications and control room indications".

Kang and Seong (2020) developed an external event PSF taxonomy for HRA. We will compare their taxonomy (divided into high level PIFs) with the existing Phoenix PIFs. It should be noted that the Kang and Seong list was developed for external hazards, without a specific focus on seismic events. Furthermore, some of the PIFs they propose do not have sufficient foundations and references in their papers, such as Gender and Age, and should be further analyzed before considering adding them to the existing Phoenix PIF set. Tables 3-5 summarize the findings, where "Example" is extracted from Kang and Seong (2020), and Phoenix equivalent presents the correspondence to Phoenix Level 1, 2 or 3 PIFs, along with their descriptions.

Tables 3a-c: Correspondence between Kang and Seong (2020) proposed PIF set for external events ("Example") for the "Individual Group" and Phoenix PIFs:

Table 3a: Temporal physical condition

Example	**Phoenix equivalent**
Fatigue	Physical Abilities and Readiness *Refers to the crew's physical capability and readiness to perform the task at hand It includes alertness, fatigue, sensory limits, and fitness for duty.*
Illness	
Hunger level	
Circadian rhythm	
Injury	

Table 3b: Emotion

Example	**Phoenix equivalent**
Panic	Stress due to Situation Perception – Stress due to Decision *Refers to the tensions/pressure induced on the team due to the perception of urgency or severity of the situation, or the awareness of the responsibility that comes along a decision.*
Embarrassment	Morale/ Motivation/ Attitude (MMA) *Refers to the team's intrinsic characteristics (including personality, temperament, style, strategy, etc.), which indicates their commitment and willingness to thoroughly complete task and the amount of effort they are willing to put into a task.*
Motivation	
Frustration	
Happiness	
Morale	

Table 3c: Cognition

Example	**Phoenix equivalent**
Situation awareness	Situation awareness is influenced by a group of PIFs - HSI, Knowledge/ Abilities, Bias, Stress, Task load
Memory	Physical Abilities and Readiness – Attention
Attention	Attention *Refers to the crew's ability to distribute the available cognitive and physical resources and it can be affected by many external distractions as well as internal thoughts and distractions (e.g., emotional state of mind of each crew member). It is comprised of attention to the current task and attention to the surroundings.*
Anticipation	Unclear, could be related to situation awareness or stress
Cognitive bias	Bias *Refers to the crew's tendency to make decisions or reach conclusions based on selected pieces of information while excluding information that doesn't agree with the decision or conclusion.*

Example	**Phoenix equivalent**
Individual decision making	(Unclear definition)

Tables 4a-d: Correspondence between Kang and Seong (2020) proposed PIF set for external events ("Example") for the "Task Group" and Phoenix PIFs

Table 4a:Team collaboration

Example	**Phoenix equivalent**
Coordination	Team Coordination *Refers to the overall ability of a team to work together as a unit to perform a given task.* _ Team Cohesion *Refers to the interpersonal interaction between the crew members and represents the group morale and attitude towards each other.* _ Team Training *Refers to how the crew members are trained on how to work with each other as members of the same team.*
Cooperation	Team Cohesion _ Team Training
Communication	Communication *Refers to the quality of the information exchanged between crew members.*
Team decision making	Team Coordination, Team Cohesion
Supervision	Leadership *Refers to the team leader's ability to set a direction and gain the commitment of the team to change / maintain goals.*

Table 4b: Time

Example	**Phoenix equivalent**
Available time	Time is modelled in Phoenix as "Time Constraint", which represents the difference between the available time and the required time to perform a task.
Time pressure	Perceived Situation Urgency *Refers to the tension / pressure induced on the team by the assessment of the speed at which an undesired outcome is approaching, or by the perception that the available time is inadequate to complete the task at hand.*

Table 4c: Task characteristics

Example	**Phoenix equivalent**
Task familiarity	Familiarity with or Recency of Situation *Refers to the perceived similarities between the current situation and the crew's past experiences, training received and general industry knowledge.* _ Task Training *Refers to the degree to which the crew is trained on the specific task so that they would have adequate knowledge/ experience/skill to perform it.*
Number of required information	Cognitive Complexity *Refers to the cognitive demands induced on the crew by the situation and assigned tasks.*
Task criticality	Perceived Situation Urgency _ Perceived Situation Severity *Refers to the tension / pressure on the crew caused by their assessment of the magnitude of an undesired outcome and its potential consequences*
High jeopardy risky task	Unclear

Table 4d: Procedure/Guideline

Example	**Phoenix equivalent**
Availability	Procedure Availability *Refers to the situation where procedures for the task at hand are in existence and accessible.*

Quality	Procedure Quality *Refers to the condition of the required procedure regarding completeness of content, ease of adherence, and appropriateness in ensuring adequate job completion.*
Level of detail	Procedure Quality
Check list	Procedure Quality _ Procedure Availability
Alternative system list	

Tables 5a,b: Correspondence between Kang and Seong (2020) proposed PIF set for external events ("Example") for the "HMI Group" and Phoenix PIFs

Table 5a: HMI

Example	**Phoenix equivalent**
Display	Human System Interface (HSI) Input *Refers to the quality of HSI concerning the input provided by the crew.* _ HSI Output *Refers to the quality of the HSI concerning the information and other outputs generated by the system for use by the crew.*
Warning light	HSI Output
Alarm sound	
Device control	HSI Input
Equipment unavailable	Tool Availability *Refers to the accessibility of the required tools to perform the task at hand.*
Hardware tool availability	
Site damage	Modeled through the Feasibility Factor, or through other PIFs, such as execution complexity due to external factors

Table 5b: Environmental condition

Example	**Phoenix equivalent**
Temperature	Execution complexity due to external factors *Refers to the physical demands induced on the crew by external situational factors and conditions.*
Noise	
Vibration	
Radiation	

As seen in Tables 3-5, the majority of PIFs proposed by Kang and Seong for external events are covered by Phoenix PIFs. Yet, the assessment of the levels of these PIFs may require modifications.

Phoenix assesses the PIF levels through questionnaires. This preliminary assessment proposes changes to the calculation of the level of the PIFs Stress and HSI. These changes are based on the work by Park et al. (2019) (Table 2). For the HSI, it is proposed that if the Damage State is 3, HSI has a probability of 1 of being degraded, since in this state most indicators and alarms are assumed to be giving misleading / wrong information. For the stress levels, the following is initially proposed, also based on the work by Park et al. (2019):

If the Damage State is 3, Stress level = 1
If the Damage State is 2, Stress level = 0.5 + 0.5(Total no. of Yes / Total no. of (Yes + No)
If the Damage State is 1, Stress level = 0.3 + 0.7 (Total no. of Yes / Total no. of (Yes + No)

Additional modifications to Phoenix PIF questionnaires include new assessment questions and examples added to existing ones:

- Procedures
  - *Does the primary procedure lack all the necessary instructions? E.g., Does the procedure provide a list of actions to be undertaken in extreme/emergency conditions?*
- Knowledge/Abilities
  - *Is the crew unfamiliar with the task? E.g., Has the crew received training for external hazard events?*
  - *Is crewmembers' physical condition impaired? (e.g., fatigued, ill, injured)*
- *Team Effectiveness*
  - *Is the crew temporarily understaffed due to personnel leaving the area because of an external hazard?*

5. Discussion and Concluding Thoughts

External events, such as earthquakes and floods, impact human performance in several aspects. They add increased pressure and stress to operators and impact the physical workspace where tasks are conducted. Typical HRA has been mostly developed and conducted for internal events, and Phoenix was initially developed for internal events performed in a control room. Yet, its framework and elements, based on a cognitive model, are suitable for external events such as earthquakes.

While deeper investigation and data collection must be performed for further development of a seismic Phoenix, it is demonstrated that the Phoenix framework provides the flexibility and adequate elements for external events. This conclusion is confirmed by recent analysis performed by Al-Douri et al. (2022), who applied Phoenix for external events. They state that "the Phoenix method is suitable for applications outside the control room." : "We were able to successfully follow the Phoenix framework to develop crew response trees (CRTs), to find failure and success paths of three decomposed ex-control room actions being examined, and to develop fault trees (FTs) for these actions that are illustrative of the types of activities conducted in human response to external hazards. Furthermore, the vast majority of CFMs presented in the Phoenix framework were found to be relevant to ex-control room manual actions."

More investigation needs to be conducted into the specific numerical probabilities associated with the CFMs added, and to characterize weighting factors that increase the impact for certain PIFs given the presence of a seismic event.

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References

J. Park, H. Jeon, J. Kim, N. Kim, S. Park, S. Lee, Y. Lee, "Remaining and emerging issues pertaining to the human reliability analysis of domestic nuclear power plants," Nuclear Engineering and Technology, vol 51, Issue 5, pp. 1297-1306, 2019.

H. Chatri, S. Yalaoui, and Y. Akl, "Human Reliability Analysis (HRA) methodologies used in the Canadian Probabilistic Safety Assessment (PSA) for external events," *PSAM 2018 - Probabilistic Saf. Assess. Manag.*, no. September, 2018.

J. Park, Y. Kim, J. H. Kim, W. Jung, and S. C. Jang, "Estimating the response times of human operators working in the main control room of nuclear power plants based on the context of a seismic event - A case study," *Ann. Nucl. Energy*, vol. 85, pp. 36–46, 2015.

Y. Kirimoto, Y. Hirotsu, K. Nonose, K. Sasou, "Development of a human reliability analysis (HRA) guide for qualitative analysis with emphasis on narratives and models for tasks in extreme conditions," Nuclear Engineering and Technology, Volume 53, Issue 2, p. 376-385, 2021.

S. Kang and P. H. Seong, "Performance shaping factor taxonomy for human reliability analysis on mitigating nuclear power plant accidents caused by extreme external hazards," *Ann. Nucl. Energy*, vol. 145, p. 107533, 2020.

N. Ekanem, A. Mosleh, & S.-H. Shen. Phoenix - A model-based Human Reliability Analysis methodology: Qualitative Analysis Procedure. *Reliability Engineering and System Safety*, *145*, 301–315, 2016.

N. Ekanem, "A Model-Based Human Reliability Analysis Methodology (PHOENIX Method)," University of Maryland, 2013.

M. Ramos, A. Mosleh, K. Nishiono, H. Ueda, & Y. Hamaguchi. "Phoenix Human Reliability Analysis Method: Application to a Feed and Bleed Operation," 2021 International Topical Meeting on Probabilistic Safety Assessment and Analysis, 2021.

EPRI, "An Approach to Human Reliability Analysis for External Events with a Focus on Seismic 2016," 2016.

C. Smidts, S. Shen, S & A. Mosleh. The IDA cognitive model for the analysis of nuclear power plant operator response under accident conditions. Part I: problem solving and decision making model. *Reliab. Eng. Syst. Saf.* **55**, 51–71, 1997.

A. Al-douri, C. S. Levine, and K. M. Groth, "Identifying Human Failure Events (HFEs) for External Hazard Probabilistic Risk Assessment," no. July 2022.