A Multi-Disciplinary Approach to Assess the Impact of Global Climate Change on Infrastructure in Cold Regions

Jim Clarke
BP Exploration, Sunbury, UK

Clark Fenton
Imperial College, London, UK

Antonio Gens
Universitat Politècnica de Catalunya, Barcelona, Spain

Richard Jardine, Chris Martin, David Nethercot
Imperial College, London, UK

Satoshi Nishimura
Port and Airport Research Institute, Yokosuka, Japan, formerly Imperial College, London, UK

Sebastia Olivella
Universitat Politècnica de Catalunya, Barcelona, Spain

Catherine Reifen, Paul Rutter, Fleur Strasser, Ralf Toumi
Imperial College, London, UK

Abstract

Imperial College London is researching with BP some potential impacts of future climate change. BP has a significant number of facilities in cold high-latitude regions, where global climate models predict significant rises in air and ground surface temperature. This could impact on the state and extent of permafrost, potentially posing risks to facilities, infrastructure, and operations (ACIA 2005). The paper reviews the research, focusing on an exemplar study region in eastern Siberia. The key elements included: (1) Developing an approach to provide a best estimate of future climate change. (2) An engineering geological appraisal of the ground conditions in the study region. (3) Performing a parametric study of geothermal conditions in the study region using finite element thermal analyses. (4) Developing a Thermal-Hydraulic-Mechanical modeling approach for assessment of climate change impact on specific engineering facilities. (5) Developing a methodology for incorporating potential climate change considerations into engineering decision-making and design.

Keywords: climate change; engineering adaptation; engineering geology; GCM modeling; Siberia; thermal modeling.

Introduction

This paper describes research by Imperial College London commissioned by BP Research. The objective was to provide BP with a process for assessing the likely effects of climate change on the integrity of its engineered facilities. The original brief was to:

- Describe the potential impact of changes in local climatic conditions on BP's current operations between now and the 2050s.
- Determine the potential vulnerability of new projects should existing design parameters remain unchanged.
- Provide a process to evaluate BP's exposure to damaging or beneficial effects of climate variability.
- Provide guidelines for the design of structures and infrastructure that anticipate potential future climactic changes in the region of interest.

A generic process has been developed to assess the potential exposure of future projects to climate change, but it became clear during the early parts of study that the outputs of General Circulation Models (GCM) used to predict climate change are not easily converted into data that can be used for engineering design. It was therefore decided to focus particular attention on the possible engineering consequences of air warming on the temperature profiles of frozen ground, the potential effects of permafrost thawing, and the difficulties of operating facilities in permafrost areas. This required the development of new modeling techniques for the assessment of climate change-induced effects on pipelines, foundations, and slopes in regions of existing permafrost.

An area of eastern Siberia was chosen as a relevant example, in order to validate the process,and to demonstrate the potential importance of climate change to BP operations.

Climate Modeling as a Geotechnical Input

The climate data used in this study is based on the predictions of seventeen coupled Atmosphere Ocean General Circulation Models (AOGCM) included in the IPCC Fourth Assessment Report (IPCC 2007), whose data is available from the Coupled Model Intercomparison Project (see URL: https://esg.llnl.gov:8443). These models were chosen because they have provided climate predictions under the conditions of the SRES A2 emissions scenario (Nakicenovic et al. 2000) adopted in this study, which is a standard pessimistic projection of greenhouse gas emission.

Coupled AOGCMs are the most sophisticated tools available for modeling current and future climate. All models used in this study have produced simulations of 20th Century climate that have been validated against appropriate contemporary observations. Climate models perform better at large spatial scales (such as global mean predictions), than at regional or local level, but there is nevertheless reasonably good agreement between modeled and observed temperature trends in Siberia and other cold regions. Careful statistical assessments indicate that the most reliable predictions are made by averaging the results of all available models to form a multi-model ensemble mean.

The multi-model ensemble mean air temperature (defined as the temperature at 2 m above the ground surface) was compared with the corresponding European Centre for Medium-Range Weather Forecasts 40 Year Re-analysis (ERA-40) observational dataset (Simmons & Gibson 2000) for each study area over the 1958–1998 period. Corrections were applied to the entire 1940–2059 time-series based on the difference between modeled and observed 40–year monthly mean temperature from 1958–1998, in an attempt to eliminate model bias as far as possible. The same process was applied to the corresponding multi-model mean time-series for snow depth. Each model time-series was then considered to correspond to the relevant 2.5° x 2.5° ERA-40 grid cell, which is equivalent to an area of approximately 150 km (east-west) by 280 km (north-south) in the study region. In all cases, the processed time-series represents a significantly larger area than would ideally be required for the thermal ground modeling, but further improvements in resolution would require better coverage of local station data than is currently available. An example of the model output is included in Figure 4, along with the predictions for changes in the ground thermal regime discussed below.

Height corrections were applied to produce both air temperature and snow depth time-series for different elevations. Temperature was adjusted based on mean monthly lapse rates derived from linear regression of the corresponding ERA-40 temperature, available for six elevations between 0 and 3000 m above sea level (m a.s.l.). Snow depth was adjusted in the accumulation phase based on a simple model describing orographic enhancement of precipitation (Roe et al. 2002), for which mean slope and wind speed data were taken from ERA-40. In the melting phase, snow depth was adjusted based on a combination of air temperature and solar radiation (Cazorzi & Fontana 1996), the former being dependent on the height correction applied to the temperature time-series. The final predicted mean monthly time-series were validated against local data and appear to be consistent with conditions in the study areas.

Project Geotechnical Strategy

The strategy developed for assessing the impact of climate change in cold regions has involved geotechnical research and development in four main areas:

1. Assessing the regional engineering geology and geomorphology of the study region, including identification of potential geohazards.
2. Reviews of present conventional frozen ground engineering practice.
3. Developing rigorous geothermal analytical tools and applying these on a regional basis.
4. Exploring and developing the potential of THM modeling in cold region engineering applications.

This work has led to a practical process for assessing geotechnical impact of climate change in cold regions that involves a hierarchy of risk assessment activities. The level of sophistication adopted for the risk assessment reflects the severity of potential adverse effects to BP's infrastructure and operations. The consequence assessment is carried out at a regional scale and incorporates consideration of the local ground conditions (identification of geohazards), the climate modeling outputs (sensitivity of hazard to climate change) and the inventory of BP's infrastructure (exposure and vulnerability).

The following three-level approach is recommended:

- Low-consequence hazards addressed through check-lists combined with simple accepted empirical methods.
- Intermediate-level cases to be tackled through regional (or site-specific) uncoupled geothermal modeling predictions combined with well-established conventional geocryological engineering approaches.
- Potentially high-consequence hazards to be addressed by advanced site-specific THM modeling.

The results obtained from any one of these approaches should confirm or challenge the initial assessment and could lead to a higher level of investigation.

Engineering Geology and Geomorphology

A region of eastern Siberia around Lake Baikal (Fig. 1) was chosen as the main focus for investigating the geotechnical impacts of climate change in an area of variable permafrost. The local geological, geographical, and climatic setting was assessed through an extensive review of published data, including geological and geocryological maps, consulting reports as well as interviews with local and international specialists. A brief reconnaissance field trip was also undertaken. The work was limited by the remote, undeveloped nature of the region. The data availability to western parties was also limited by a combination of material sensitivity, geographic location of resources, and translation requirements. A good data set is crucial to the recommended process and, to progress this study, the current assessment was augmented by reference to data from analogous geological and geocryological settings around the world.

Data requirements

The inputs needed to assess the geotechnical impact of climate change on permafrost are driven by the requirements of the geothermal modeling analyses discussed below. The key data requirements are:

- Comprehensive local climate records.
- Geographical and geomorphological information.

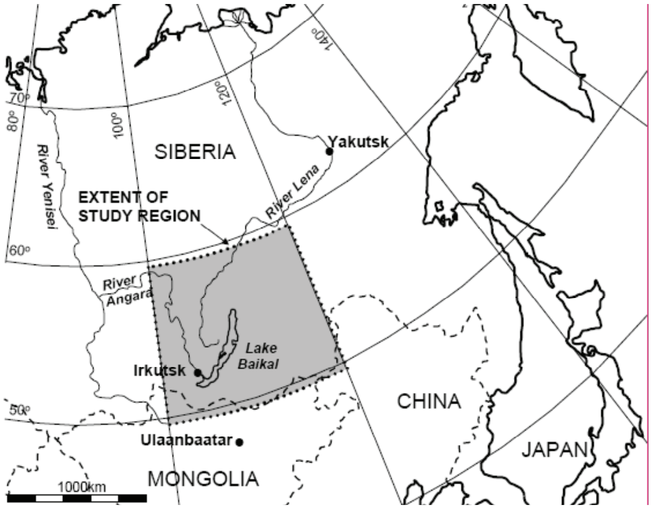

Figure 1. Study region and vicinity map.

- Surface and deeper geology.
- Geocryology, including ground thermal regime and geothermal material properties.
- Land use and forest fire records.
- Inventory of relevant infrastructure.

Regional setting of study area

Ground conditions vary considerably over the area selected for detailed study, which is outlined in Figure 1 and measures approximately 1300 km east-west and 1100 km north-south. The topography ranges from high-relief mountains (Baikal, Patoma, and Khamar Daban ranges) to low-lying fluvial plains towards Mongolia and along the Angara River valley. The geology varies from relatively flat-lying undisturbed sedimentary rocks of the Siberian platform, to much older highly deformed and metamorphosed rocks along the active Baikal rift zone. The significant variation in relief has a profound effect on the observed climatic conditions, the vegetation, drainage characteristics, and hence the permafrost distribution within the region, which varies from being absent to continuous.

Geomorphological units and expected ground conditions

In order to assess the ground conditions across the study region, five geomorphological units were defined, which encompass broadly similar physical characteristics, as shown in Figure 2.

Once these geomorphological units were defined, five "exemplar" study areas were selected (Fig. 2), which provided representative settings for the associated climate modeling, geothermal ground modeling and engineering geological terrain analysis.

Remote sensing data (Shuttle Radar Topography Mission [SRTM] topographic survey data) was used to produce a Digital Elevation Model (DEM), allowing detailed assessment of elevation, slope angle, slope aspect, and drainage characteristics within each study area. This terrain analysis could be further enhanced in future applications by incorporating higher resolution datasets.

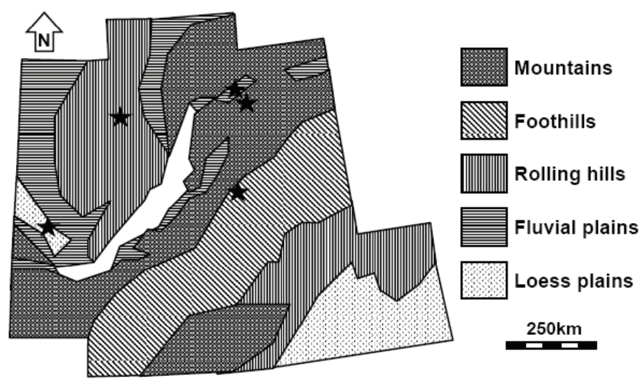

Figure 2. Classification into five geomorphological units. Black stars show location of "exemplar" study areas.

Geological, geocryological, and geotechnical characteristics were interpreted for each study area, based on literature review and field reconnaissance, assigning data where necessary from other global analogues. The latter included representative vegetation and ground void ratio profiles for each study area, which provided best-estimate, lower-bound, and upper-bound parameters for geothermal numerical modeling in each setting.

Although this investigation has included a thorough review of all of the readily available data, there is significant uncertainty associated with the age, provenance, and hence accuracy of some of the available information. The current review is considered adequate for a preliminary research study, which could be compared with the feasibility or possibly appraisal stage of a large civil engineering project. However, detailed site-specific information and further analysis would be essential before progressing to any preliminary design stage.

Geocryological Engineering

Civil engineering activity in the North American cold regions prompted rapid development from the 1960s of specialist geotechnical tools, analyses and practices, as detailed in Andersland & Ladyanyi (2004), for example. Similar work was undertaken from an earlier date in the Former Soviet Union, although much of the output was published in Russian and is less well known in the West. The paradigms, practices, and design codes applied in North America and the Former Soviet Union are substantially different.

Some of the practical geocryological engineering topics that are important to the proposed risk assessment and design processes are highlighted below.

Geocryological analysis: elements, options, and strategy

Geocryological engineering analysis involves many elements; the relative significance of which depends on the nature of the engineering problem of interest. For example, thermal (T), hydraulic (H), and potentially chemical (C) elements are more important than the mechanical (M) element in water discharge or contaminant transport problems. However, it is essential to address the mechanical element when assessing the viability, stability, and serviceability of facilities, pipelines and slopes.

Checklists, definitions, and indices

The essential precursor for all rational geocryological analyses is the information gathering and data access. Geothermal modeling is only possible when adequate climate, geology, and ground temperature data exist, including the local air-to-ground temperature conversion factors, which are influenced by local vegetation, soil types, topography, and weather patterns.

Ground behaviour associated with thermal regime changes

Engineering activities and climate change trends are both likely to modify the ground's thermal regime. Significant deterioration of the engineering properties of frozen soil is expected as temperatures increase, potentially leading to difficulties with embedded structural elements such as foundations and pipelines. Potentially severe phenomena may be encountered in soils or rocks that become unstable as they thaw. It is also well known that frozen soils show very strongly time-dependent behaviour: creep movements can be large in the field and field strengths may be far lower than are seen in laboratory loading tests.

Furthermore, the thawing of frozen open ground can lead to substantial settlements and large transient pore-water pressures. In cold regions, slope stability is dominated by thermal effects. Slopes sited in permafrost areas experience annual cycles of thawing and freezing in their active layers, experiencing seasonal downslope creep. Large-scale instabilities can also occur as a result of changes in ground surface conditions or sub-surface hydrology.

Construction itself may generate more significant thermal changes in foundation soils and rocks than those expected from climate change alone. Insulation elements, air ducts, or active cooling systems are often designed and installed to improve foundation behaviour, and these could be required more extensively to cope with climate change.

A key issue in pipeline engineering is the effect on the ground thermal regime of heat flow to or from the pipeline and its products. Thawing induced by running warm oil in pipelines buried in frozen ground can induce melting, settlement, strength loss, and even floatation. Elevated sections may be utilised, but these require piled foundations that can cope with the possible geotechnical consequences of climate change. On the other hand, ice migration and growth caused by running chilled gas in buried unfrozen ground can cause serious differential heave in pipelines installed in discontinuous permafrost regions. It is therefore vital to consider all potential damage processes within the risk assessment process.

Thermal Modeling and Permafrost Mapping

In order to make reasonable assessments of how slopes, foundations and pipelines may respond to climate change, it is necessary to be able to reliably predict how ground temperatures and properties will react over tens of metres of depth. GCM models incorporate sophisticated formulations that address temperature variations within the atmosphere and oceans, and offer projections as to how the climate may change in the future. However, the near-surface temperature of the ground is usually considered in a simplistic manner, for example, by assuming a constant ratio between air and ground temperature changes, and little attention is given to what may happen at greater depths. The GCMs therefore fail to predict the considerable time lag between climate change and ground response, potentially resulting in gross overestimates of the depth of permafrost melting expected by any given date, the degree of ground warming, and, therefore, of permafrost degradation and infrastructure distress.

Simple models have been proposed to relate air and ground temperatures; however, the Authors' work has shown that the thermal conductivity is complex and nonlinear in permafrost, and a fundamental analytical treatment is necessary to predict the variations with time of the thermal regime, extending tens of metres beneath the ground surface. A fundamentally formulated regional approach has been developed for the present study. A new Finite Element Code (FEM FATALE, Nishimura 2007a) was written to perform rigorous thermal analyses efficiently for multiple vertical profiles. The code can also be applied to any other specific site, for which detailed information is available.

The model is based on non-linear heat conduction theory, with material properties that effectively vary with unfrozen water content and hence temperature. The thermal properties of water, ice, and the soil minerals are fixed, and the global properties at any point in the ground profile depend on the ground's porosity profile (which is input on the basis of the engineering geology assessment described above) and a specific function that relates the degree of ice saturation to temperature. The code also incorporates latent heat effects. The effects of the seasonally-variable snowcover are modeled explicitly. The surface energy transfer is modeled using the n-factor approach (Lunardini 1978), making careful distinctions between summer values and times when the ground is snow-covered, when n is taken as unity. These purely thermal regional analyses do not consider pore fluid migration or ground deformations; these features are covered by the more sophisticated, fully-coupled THM approach reported later.

The purely thermal approach has been applied on a regional basis by considering multiple analyses of the development of permafrost in the circum-Baikal region, covering the period 1940 to 2059. Climate predictions have been applied to stereotypical ground profiles that were selected to encompass the range of geological/geotechnical conditions that might reasonably be expected within the five geomorphological units in the study region. An extensive parametric study has been performed with FEM FATALE to produce time-series predictions for ground temperature and ice content profiles from ground level to 100 m depth, considering the effects of different surface elevations, porosity profiles, snow cover, and natural geothermal gradients; the output data providing the basis of a large-scale risk assessment process for climate change-induced hazards. Examples of some predictions are shown in Figures 3 and 4; substantial warming and thawing is indicated over the next 50 years within

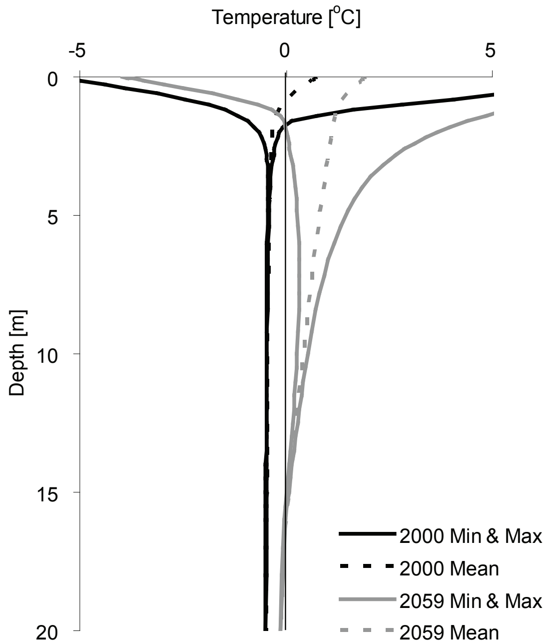

Figure 3. Example of simulated geothermal curves: case of stratigraphy with 1 m colluvial soil (assumed porosity, ∅ = 0.4) and 9 m weathered rock (∅ reducing from 0.4 to 0.04 with depth) overlying base rock (∅ = 0.04) in the rolling hills study area, 643 m a.s.l. (assuming air-surface thawing index, n_t = 0.6).

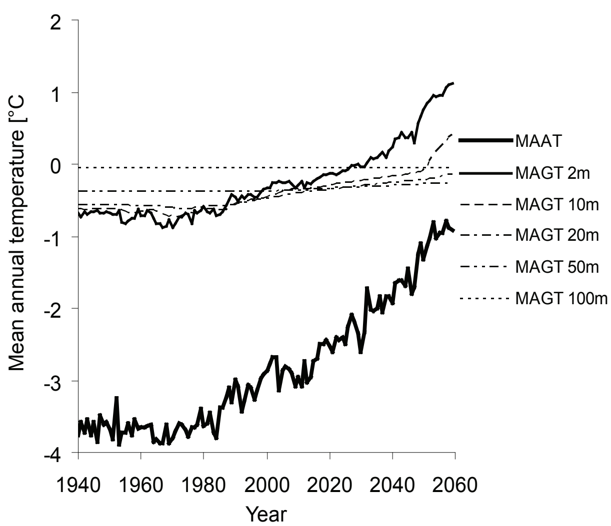

Figure 4. Predicted time-series of temperature at different depths, for example shown in Figure 3.

the top 20 m that would have a considerable negative impact on foundations, pipelines, and slopes.

In addition, a new method has been developed for correlating, synthesising, and presenting the time-dependent evolution of geocryological conditions in a series of layered maps. The approach interfaces data from DEM and GCM sources with the FEM FATALE thermal analyses. The approach has been used to successfully predict, from first principles (i.e., "Type A" prediction, Lambe 1973), the current and historical extent of permafrost in each geological study area, and can be used to produce maps of future distribution of permafrost and its thermal characteristics. Engineering geocryological analyses may be performed based on these data to predict the geotechnical impact for a particular facility or area.

Fully-Coupled Finite Element Analysis

In cases where the consequences of the expected ground temperature changes are sufficiently significant, more rigorous THM analyses of the interconnected thermal (T), hydraulic (H) and mechanical (M) processes may be deemed necessary. THM analyses incorporate predictions for ground movements, soil stresses, and changes in state, along with possible ground failure and soil-structure interaction. While THM models offer potentially powerful tools for assessing climate change impact, they are rarely conducted in practice: their complexity, incompletely developed formulation, and long computational run times limit their current appeal. Assessing, developing, and demonstrating THM applications in cold region geotechnical engineering was an important aspect of the present study, even though THM analyses are likely to be reserved for high-consequence cases.

THM-analysis has been developed intensively for high-temperature problems, particularly related to nuclear waste disposal. However, its application to frozen soils has concentrated on frost heave, and its potential use in permafrost problems has only been noted recently. The group collaborated with colleagues at UPC Barcelona for this purpose, running and developing with them their sophisticated THM programme CODE-BRIGHT (Olivella et al. 1996, Gens 2008). The main aims of the THM component of the study, and the achievements made, were:

- An assessment of the difficulties in applying THM-analysis to permafrost problems. Potential problems have been identified and solutions found that will enable a wider range of applications.
- Developing a robust overall THM modeling framework capable of embracing future sub-model developments. The formulation requires additional features that are important in ice-rich permafrost, including the development of large creep strains under load and the potential for extreme pore pressure generation during thawing.
- A new framework of describing stresses in frozen soils. This development has opened a way for recently developed soil model elaborations to be directly applied in frozen ground modeling.
- Successful back analyses of practical pipeline frost heave problems, which demonstrate the potential for THM analysis in cold region engineering applications.

Freezing ground water migration problems such as frost heaving around chilled pipelines can be simulated with reasonable accuracy by the CODE-BRIGHT model in its current state; the case study outlined below is provided as an illustration. THM analyses undertaken with the code for this project provide good predictions of the frost heave measured in a carefully controlled, long-term field test involving chilled gas running in a frost susceptible unfrozen silty soil (Slusarchuk et al. 1978). Figure

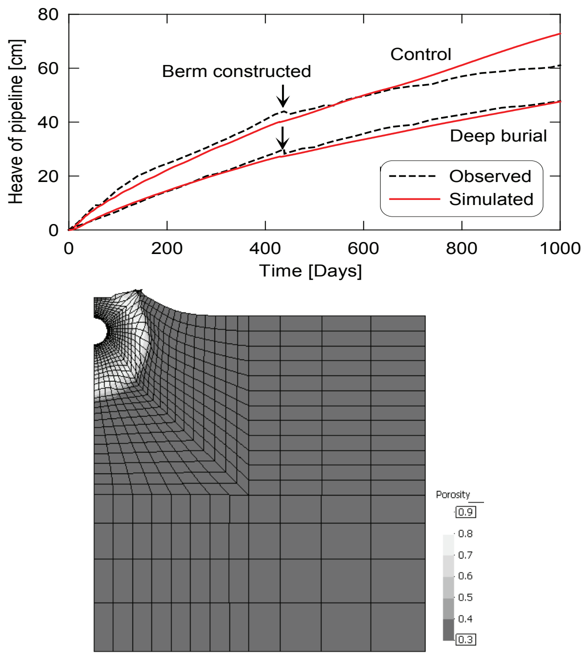

Figure 5. Top: Comparison between observed and measured heave of pipeline buried at two different depths. Bottom: Deformed mesh showing simulated pipeline heave and porosity contours in "Control" case at day 1000.

5 shows the generally good agreement between the observed and simulated heave of pipelines buried at two different depths; 'Control' and 'Deep burial' (Nishimura 2007b).

The THM model's fully-coupled treatment allows far more generalised situations to be considered than conventional engineering geocryological methods. Three-dimensional soil-structure interaction in discontinuous permafrost can be considered, in principle, without many additional modifications.

Conclusions

- A multi-disciplinary approach has been developed to assess the impact of climate change on infrastructure; this has been applied in an exemplar cold region of eastern Siberia.
- The effect of air temperature change on ground temperature profiles has been identified as being of critical significance to facilities and ground conditions in areas of variable or discontinuous permafrost.
- An integrated regional assessment approach has been developed that combines climate modeling data, engineering geology assessments, remote sensing data, and geocryological engineering methodologies to produce regional ground condition predictions.
- More advanced fully-coupled THM approaches have also been explored for site-specific application in critical cases. Key development targets have been identified for future THM modeling research.
- The research predicts that climate change will have a considerable impact on ground conditions in the study region over the next 50 years. However, the effects will be less severe than might be anticipated from studies that do not model the ground response with the same level of sophistication.

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