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SEISMIC HAZARD ASSESSMENT WITH THE AID OF EMPIRICAL GREEN'S FUNCTIONS

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ABSTRACT

The method of empirical Green's functions (megf) was applied to the assessment of seismic hazard associated with the gas production from a natural gas field in south-western France. The main problems that were encountered are discussed from an engineering point of view. It is emphasised that uncertainties particularly in the moment-magnitude relationship as well as in the determination of corner frequencies and stress drop can impair the reliability of the results. In order to get rid of numerical artefacts, a hybrid method was adopted: the simulated accelerogramms were low-pass filtered, and a suitably modulated high frequency noise was added. It is concluded that the megf, *when used with caution*, can provide useful results. However, before the megf can be regarded as an engineer's tool for hazard studies, the authors feel that the influence of model and parameter uncertainties on the final results should be investigated in more details.

KEYWORDS

Empirical Green's functions; seismic hazard assessment; induced and associated seismicity; hydrocarbones production; gas field.

INTRODUCTION

The goal of the present contribution is to present an application of the method of empirical Green's functions (megf) to an industrially relevant situation. A formulation of the megf according to Irikura (1986) was used. Owing to space limitation, neither a complete literature review nor a presentation of the several kinds of formulation will be given; the reader is referred to the relevant literature (e.g. Joyner and Boore, 1986; Gariel and Mohammadioun, 1991; Hutchings, 1994; Irikura and Kamae, 1994; Tumarkin and Archuleta, 1994).

For readers who are not familiar with the megf, the method is shortly described in the next paragraph. Further paragraphs present the industrial and geophysical context as well as the main problems that were encountered. Finally, some results are given and discussed.

A QUALITATIVE DESCRIPTION OF THE METHOD

In linear elastodynamics, the displacement-time field due to an unit impulsive point load, precisely defined in both space and time, is called Green's function. The displacement-time field due to the same type of load at the same location, acting for a finite time, can be found by convolution of the Green's function.

The basic idea of the megf, first put forward by Hartzell (1978), is to interpret the instrumentally measured response to a small seismic event as an "empirical Green's function" (egf) and to convolute it suitably in order to simulate the response to a moderate or large earthquake. The "small" event should be infinitely small in order to originate from a "point fault" and thus to really represent a Green's function. However, the small event must be strong enough in order to generate amplitudes at low frequencies well above both ground noise level and instrumental resolution. In practice, the event is only small with respect to the target event.

Hartzell's idea has since been further developed by numerous scientists. The egf is taken at several times and added up so that a larger earthquake of the same focal mechanism and hypocentre is synthesised. The repeated small events are thought to be distributed over a hypothetical fault whose size corresponds to what is expected for a larger earthquake (the "target" event). Time delays are introduced between the repeated events that roughly simulate a physically realistic rupture process across the hypothetical fault. The number of added events as well as the way the summation is done are deduced from scaling relations of source parameters and scaling laws between earthquakes of different size. A schematic representation is given in Fig. 1.

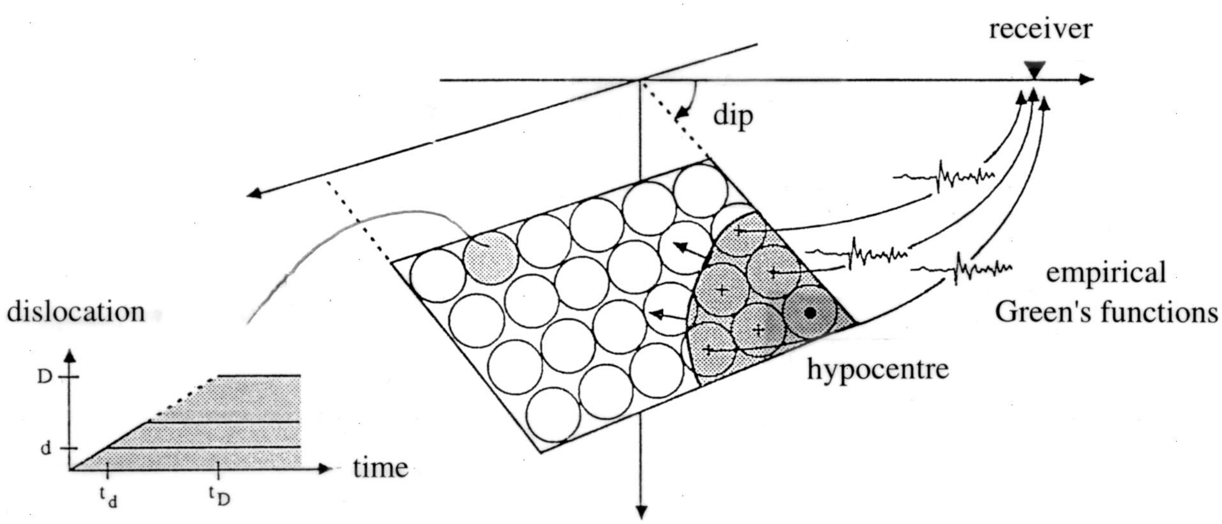

Fig. 1: Schematic representation of the different sources of time delays in the summation of the egf: path length, finite rupture velocity and dislocation rise time (after Bour, 1993).

For site hazard studies, the main advantage of the megf is that propagation path and local site effects, and to some extent the radiation characteristics of the source, are all so to speak measured and therefore accounted for in a significantly more precise manner than by classical approaches. Assumptions have to be made with regard to the source function of the target event. Its spectral content is usually deduced from the so-called ω^{-2}-spectral scaling model (Aki, 1967), which is empirically well established for the magnitude range of about ~ 2.5 < M_l < ~ 7.5. Often, the assumption of identical stress drop for both the small and the target event is adopted; otherwise, it is easy to correct for different stress drops by simply multiplying the Green's functions by a corresponding scalar (Irikura and Kamae, 1994). The main unknown parameter is the rupture process (hypocentre location, shape and velocity of rupture front), but this corresponds to a physically inherent uncertainty that exists independently of the method as such.

Many seismologists have checked the method by applying it to pairs of aftershocks of considerably different size. In most of the cases, they were able to find a certain realistic rupture process that lead to an astonishing resemblance between the synthesised and the recorded large aftershock. However, it is worth noting that they usually limited themselves to relatively low frequencies (say below a few Hz) and often worked in terms of velocities rather than accelerations. In fact, as will be shown later, it is usually at the "higher" frequencies, but still within the range that interests structural engineers, where numerical problems may arise.

THE CONTEXT OF THE LACQ GAS FIELD

Geophysical aspects

The Lacq gas field, 200 km south of Bordeaux (France), is situated on the northern foothills of the Pyrenees mountain chain, very close (2 km) to the shallow and seismically inactive "North Pyrenean Overthrust" (Fig. 2). About 30 km further south is the "North Pyrenean Fault", which is active and responsible for the seismic activity in the Pyrenees down to a depth of 20 km. The reservoir consists of Jurassic dolomite. It is located in an anticline that extends 16 km east-west and 8-9 km north-south. The thickness of the reservoir is about 500 m and the top is located at a depth of 3200 m below the surface (Maury *et al.,* 1992).

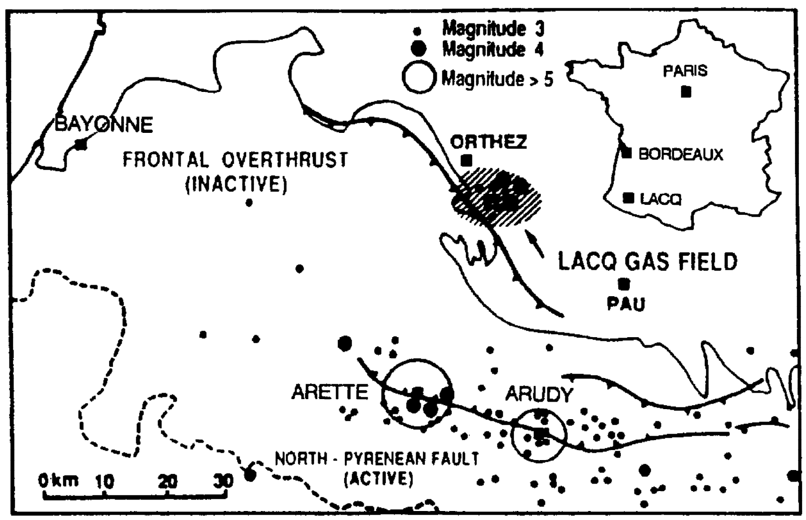

Fig. 2: Location of the gas field (shaded area), seismicity (black dots: M_l < 5; open cirles: M_l > 5) and local geologic structure (heavy lines), after Maury *et al.* (1992).

Gas production started in 1959 at an initial pressure of 64 MPa. Until 1969, which corresponded to a pressure drop of 30 MPa, no sign of local seismic activity was observed. Seismic events were first felt in 1969 and 1972, with estimated magnitudes between 3 and 4. It was then decided to monitor the seismic activity: more than 800 tremors with magnitudes ranging from 1.0 to 4.2 could be recorded within the first ten years of monitoring (Grasso and Wittlinger, 1990). Nearly all of the epicentres were located within the lateral extent of the gas field. The only perturbation of the stress or strain fields, which has the same spatial and temporal scale as the observed seismicity, is the 500 bar (50 MPa) drop in gas pressure due to 20 years of gas exploitation, demonstrating that these events were associated with the gas pressure decline. In 1990, the pressure at the top was measured at 9 MPa.

Seismic risk

Around the gas field, chemical industries have developed that store and process significant quantities of highly inflammable, explosive or toxic gases, and in 1990, public authorities expressed their concern about seismic risk. Since there was no historical seismicity in the immediate surroundings (the active North Pyrenean Fault is 30 km away), Lacq was classified zone zero by the French natural seismic zonation in use. Zone zero is the country's lowest seismic hazard. However, in view of the newly observed local seismic activity, this did no longer seem to correspond to the actual situation. Thus, the public authorities asked for a study that would investigate whether the area had to be reclassified in a zone of higher seismic hazard.

Since the industrial facilities of interest were situated at distances as small as 2 to 5 km from the epicentres of the observed seismicity, and the focal depths were at only 4 to 5 km for most events, the use of classical attenuation laws for the hazard evaluation would have been questionable. The attenuation laws are hardly reliable within this range due to the lack of sufficient nearfield acceleration data. That's why it was decided to apply the megf, although no engineering experience with the method seemed to exist in Europe so far. An accelerometric, "moderate strong motion" monitoring with four accelerometers of the type Lenartz 5800 (3D-sensors Guralp CMG5) was run during two years. These accelerometers were installed in addition to the already existent telemetric network of (velocity) seismometers (Grasso and Wittlinger, 1990). The recorded accelerometric data were then used as empirical Green's functions.

Maximum credible local earthquake

The megf is an inherently deterministic approach. Ground motions can be calculated for an earthquake of given characteristics at a given depth and distance from the site of interest. This was judged to suit the French practice which is to consider a kind of deterministic maximum credible earthquake as relevant for the design of industrial facilities classified as "with special risk". Therefore, a maximum credible magnitude of induced seismicity had to be estimated.

Through a careful relocalisation of more than 300 events with the aid of a 3D velocity model, it was possible to show that the hypocentre formed a diffuse zone that mimics the local dome structure of the gas field. No event was localised on the nearby North Pyrenean Overthrust. This was a crucial result since otherwise, if the overthrust had had to be considered as reactivated, rather large maximum magnitudes would have had to be considered owing to the overthrust's regional dimension. Two further well established facts finally allowed to limit the maximum credible magnitude to a value of $M_l = 4.5$ (Grasso, 1993). First, it was known from numerous drillings that the brittle, potentially seismogenetic layers were not thicker than 500 m. Second, the shape of the magnitude-frequency relationship of about 1000 seismograph records of $1.0 \leq M_l \leq 4.2$ showed a clear resemblance to well observed seismicity associated with volcano activity. This allowed to conclude in analogy to a limited dimension of the seismogenetic structures (Volant and Grasso, 1994)

CALCULATIONS

For constant stress drop, Aki (1967) proposed a scaling law of the form $M_0 \sim L^3$, where L is a characteristic linear dimension of the fault, e.g. its length. This leads to a linear scaling factor between a large ("target") and a small ("Green's") event of

$\alpha = [M_0(\text{target})/m_0(\text{Green})]^{1/3}$,

i.e. the length and width of the fault as well as the final slip are assumed α times larger for the target event than for the Green's one. If both events show a ω^{-2}-decay of the displacement spectra, as is usually assumed (Aki, 1967), then the following spectral ratios result (see Fig. 3): M_0/m_0 for $f < F_c$ (F_c: corner frequency of the target event), $[M_0/m_0]^{1/3}$ for $f > f_c$ (f_c: corner frequency of the Green's event), with a ω^{-2}-decay in between.

Principal Uncertainties

M_0 - M_l relationship. As was shown above, a reliable "transposition" of magnitudes into seismic moments is a fundamental step within the megf. Current M_0 - M_l relationships are of the form

$\log (M_0\,[\text{Nm}]) = p\ M_l + q$,

with a value of p usually around 1.5 for moderate to large ($M > 5$) earthquakes (Kanamori and Anderson, 1975). However, Feignier (1989) had found for the small Lacq events $p = 0.34$. This value being far below anything published so far was considered as inappropriate for a hazard evaluation. Therefore, the following relationship was used:

$\log (M_0 \text{ [Nm]}) = 1.0 \ M_l + 10.$

This coincides well with relationships established for small events ($0.8 < M < ...$) in the Swabish Jura and in the Friuli. These relationships are beyond those with the lowest published p-values. Attention is drawn to the fact that the exponential characteristics of the M_0 - M_l relationship renders the p-value a highly sensitive parameter for hazard evaluation. Evidently, the same holds good for the magnitude itself, although this is only a problem if incoherent magnitude values (for instance local magnitudes determined by different laboratories) are used.

Determination of corner frequency. As can easily be seen from Fig. 3, which is a loglog representation, any uncertainty in the determination of the "exact" value of f_c corresponds to a potential horizontal shift of the straight line representing the ω^{-2}-decay. This leads to a significant uncertainty in the hazard determination, most often within the frequency range of primary interest to structural engineers.

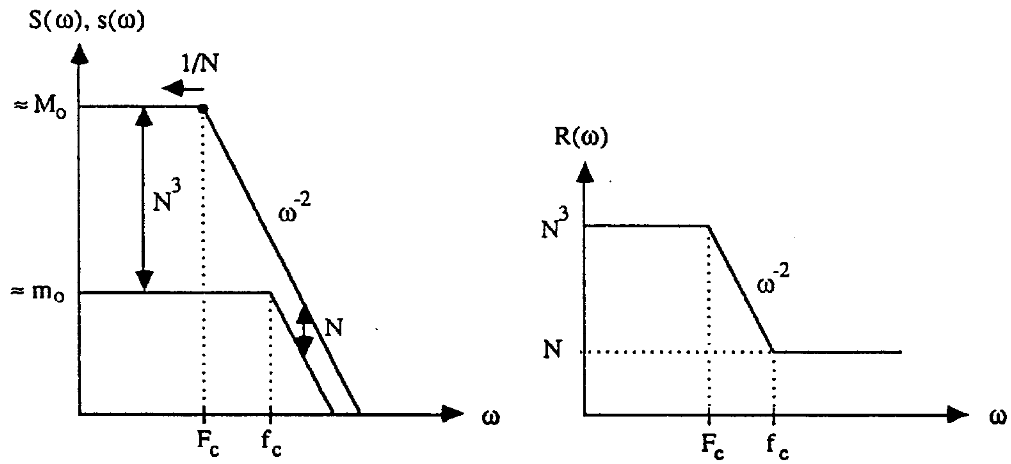

Fig. 3: Theoretical displacement spectra of Green's and target events under the hypothesis of ω^{-2}-spectral decay; theoretical spectral ratio $R(\omega)$ (after Bour, 1993).

Stress drop. Currently, stress drop is calculated through $\Delta\sigma \propto M_0/L^3$. The fault dimension L is usually regarded as proportional to $1/f_c$ (e.g. Brune *et al.*, 1979). The proportionality constants depend on geometrical and material parameters. Thus, the determination of the stress drop is highly sensitive with respect to any uncertainty in the determination of the "exact" corner frequency, since errors are put into the third power. However, if a given stress drop is aimed at for the target event, this "stress drop sensitivity" partially compensates the afore-mentioned direct sensitivity with respect to f_c. For the present study, it was assumed that the stress drop was the same for the Green's and the target event.

Rupture parameters. In contrast to the above mentioned model uncertainties, rupture parameters (point of nucleation, velocity, propagation direction, focal mechanism) are inherently unknown. These parameters were therefore varied within "reasonable" limits in the context of a sensibility study. The most important influence could be observed from directivity effects due to opposite rupture propagation directions.

Numerical Problems

Numerical artefacts. The discrete summation of elementary sources in space and time leads to unphysical frequency contents within the simulated accelerograms, to so-called numerical artefacts. Particularly difficult to get rid of is the "fundamental spatial artefact" with a frequency around v_r/l_c, where v_r is the rupture velocity and l_e the dimension of the spatial grid (fault length of the Green's event). This value is normally somewhat higher than f_c, but still within the frequency range of interest to structural engineers. The most obvious way to overcome this problem seemed to be the introduction of either a stochastic rupture velocity or a stochastic disturbance of the spatial grid. However, the experience of Bour (1993), namely that these artefacts never fully disappeared, was confirmed in the present study. Since the artefacts could lead to completely erroneous results at high frequencies, it was decided to resort to the hybrid method described below.

Low frequency noise. Because of the low magnitudes ($1.4 < M_l < 2.9$), the accelerometric recordings inevitably showed a poor signal-to-noise ratio at low frequencies ($f < 0.5$ Hz). Therefore, the recordings were filtered at very low frequencies in order to establish the theoretically correct acceleration spectral growth with ω^2.

A Hybrid Method

In order to get rid of numerical artefacts, a pragmatic hybrid method was adopted in the following way:
- the lowest possible artefact frequency f_a was evaluated with directivity effects taken into account
- the simulated target accelerogram $u_t(t)$ was low-pass filtered with a cut off frequency slightly below f_a; this lead to $u_t^{lf}(t)$
- the envelope of the target accelerogram was calculated with the aid of the Hilbert transform
- based on the corner frequency f_c of the Green's event and the theoretical spectral ratio between target and Green's event (Fig. 3), the theoretically expected spectral shape of the target event was determined
- a broad-band noise signal was modulated so that it finally corresponded to the theoretical target spectral shape as well as to the above calculated envelope in time: $u_n(t)$
- $u_n(t)$ was suitably high-pass filtered, which gave $u_n^{hf}(t)$
- finally, the hybrid final result was given by $u_h(t) = u_t^{lf}(t) + u_n^{hf}(t)$

It is felt that in $u_h(t)$, no deterministic physical information is lost. Spectral shape and duration of the resulting accelerogram correspond to what results from the application of the unmodified megf. On the other hand, in the context of a real forward prediction, it can never be expected that the high frequency time signal has any deterministic physical significance. A blemish of the hybrid method is only that it is not adequate for backward predictions: It is no longer really possible to adjust the rupture parameters so that a good time signal resemblance is obtained between a simulated and a measured target event (except for only the low frequency part and the envelope), since usually, the high frequency content optically dominates the time signal.

RESULTS

Eight different recordings were used as Green's functions for the Lacq study. As an example, Fig. 4a and 4b show a Green's function and a corresponding synthesised accelerogram respectively (N-S and E-W components). As expected, a shift of the dominant frequencies towards lower values is evident.

Each Green's function was convoluted in ten different ways through variations of the unknown or vague source parameters (changes in rupture nucleation, propagation direction and velocity; variations of strike and dip; variation in rise time). Figure 5a shows the response spectra (for both horizontal components) of all the synthesised accelerograms obtained from the Green's function given in Fig. 4a. Finally, Fig. 5b shows the mean response spectra per Green's function that was used.

It seems interesting to note that the physical variations in the rupture process as well as the use of different Green's functions resulted in scatters that, roughly speaking, were of the same order of magnitude as what is currently observed in classical spectral attenuation laws. For arguments that will not be exposed here, the mean of the three unfavourable curves was chosen as relevant for the hazard definition with respect to the local associated seismicity.

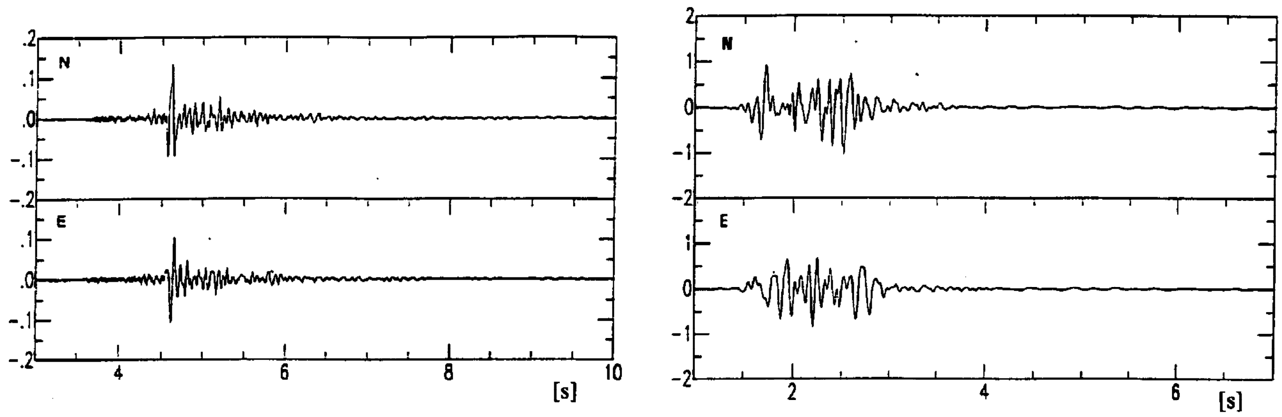

Fig. 4: (a) One of the empirical Green's functions used, in m/s^2; (b) a set of accelerograms, in m/s^2, synthesised with the egf shown in (a).

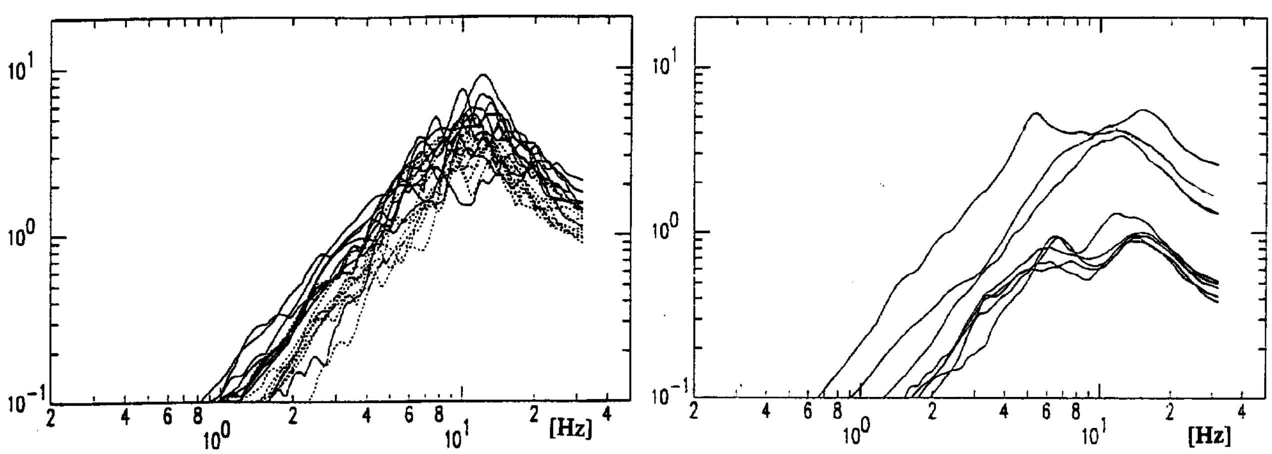

Fig. 5: (a) Cloud of response spectra of accelerograms synthesised on the basis of the egf of Fig. 4(a), for varied source parameters, in m/s^2; (b) Mean response spectra of the accelerograms synthesised with varied source parameters, in m/s^2 (one curve per egf that was used).

CONCLUSIONS

Despite the reported uncertainties and the strict limitation to linear site behaviour, it is concluded from this study that the megf, *when used with caution*, can provide useful results: the physical origin of many of the uncertainties is relatively well controlled, probably better than for those arising in the use of empirical attenuation laws. This seems particularly true in the case of moderate magnitude, short distance shallow events.

However, before the megf can be regarded as a practical tool for site hazard studies, the influence of all kinds of model and parameter uncertainties on the final results should be better investigated. Furthermore, the scatter of results obtained with classical attenuation laws and with the megf should be compared by means of systematic studies.

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